ERDC TR-00-3

US Army Corps of Engineers®

Multiuser Disposal Sites (MUDS) for Contaminated Sediments from Puget Sound—Subaqueous Capping and Confined Disposal Alternatives

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July 2000

Engineer Research and Development Center

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PRINTED ON RECYCLED PAPER

ERDC TR-00-3
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Multiuser Disposal Sites (MUDS) for Contaminated Sediments from Puget Sound — Subaqueous Capping and Confined Disposal Alternatives

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Final report

Prepared for U.S. Army Engineer District, Seattle
Seattle, WA 98124-2255

Engineer Research and Development Center Cataloging-in-Publication Data

Multiuser disposal sites (MUDS) for contaminated sediments from Puget Sound : subaqueous capping and confined disposal alternatives / by Michael R. Palermo ... [et al.] ; prepared for U.S. Army Engineer District, Seattle.

201 p. : ill. ; 28 cm. — (ERDC ; TR-00-3)

Includes bibliographic references.

1.Contaminated sediments — Environmental aspects —Washington (State) — Puget Sound Region. 2. Dredging spoil — Environmental aspects — Washington (State) — Puget Sound Region. 3. Dredging — Management — Washington (State) — Puget Sound Region. I. Palermo, Michael R. II. United States. Army. Corps of Engineers. Seattle District. III. Engineer Research and Development Center (U.S.) IV. Environmental Laboratory (U.S.) V. Coastal and Hydraulics Laboratory (U.S.) VI. Series: ERDC TR ; 00-3.

TA7 E8 no.ERDC TR-00-3

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Preface

The U.S. Army Engineer District, Seattle (CENWS), is participating in the Puget Sound Confined Disposal Site Study, which is aimed at determining the feasibility of establishing a system of multiuser disposal sites (MUDS) for disposal of contaminated sediments dredged from Puget Sound. Most of the contaminated sediments within Puget Sound are located within the central portion of the sound and are associated with environmental cleanup projects directed through Federal or state enforcement actions, projects with restoration of aquatic habitat as their primary purpose, and dredging of Federal and non-Federal navigation channels.

The feasibility evaluation will be conducted in phases. The initial programmatic phase resulted in a Programmatic Environmental Impact Statement (PEIS). Site-specific evaluations along with a site-specific EIS will be conducted in subsequent phases. Disposal alternatives that were evaluated include: (a) level bottom capping and contained aquatic disposal (CAD), (b) nearshore (or island) confined disposal facilities (CDFs), (c) upland CDF disposal, (d) disposal in solid waste landfills, and (e) multiuser access to larger fill projects.

CENWS requested support from the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, in conducting the feasibility evaluations. This report describes various subaqueous capping and confined (diked) disposal alternatives and provides conceptual designs and design and performance standards for these alternatives.

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The authors acknowledge the contributions of Dr. George Turk, CHL, and Dr. Mary Ellen Hynes, Geotechnical Laboratory, ERDC.

At the time of publication of this report, Dr. Lewis E. Link was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

This report should be cited as follows:

> Palermo, M. R., Clausner, J. E., Channell, M. G., and Averett, D. E. (2000). "Multiuser Disposal Sites (MUDS) for Contaminated Sediments from Puget Sound—Subaqueous Capping and Confined Disposal Alternatives," ERDC TR-00-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

1 Introduction

Disposal Alternatives

The dredged material disposal options being considered for Puget Sound contaminated sediments include no action, variations of confined (diked) disposal, subaqueous capped or contained aquatic disposal, disposal in solid waste landfills, and combinations of these alternatives. A conceptual cross section showing the relative configurations of the disposal alternatives under consideration for multiuser disposal sites (MUDS) is shown in Figure 1. The no-action alternative, placement in solid waste landfills, and combinations of alternatives are being developed by others under the overall MUDS study framework. Disposal alternative descriptions, conceptual designs, and testing and monitoring considerations are presented in this report for subaqueous capping, confined aquatic, and confined (diked) disposal alternatives.

Confined (diked) disposal is placement of dredged material within diked nearshore or upland confined disposal facilities (CDFs) via pipeline or other means. The term CDF is used in this document in its broadest sense. CDFs may be constructed as upland sites, nearshore sites with one or more sides in water (sometimes called intertidal sites), or as island containment areas (U.S. Army Corps of Engineers/Environmental Protection Agency (USACE/EPA) 1992). Subaqueous capping is a disposal alternative involving placement of contaminated material at an open water site followed by a covering or cap of clean isolating material. Level bottom capping (LBC) is placement of the contaminated material and cap in a mounded configuration on a natural bottom. Contained aquatic disposal (CAD) is similar to LBC but with the additional provision of some form of lateral confinement (e.g., placement in bottom depressions, or behind subaqueous berms).

The design of CDFs, CAD sites, and similar sites for disposal of contaminated sediments under the MUDS framework must consider the appropriate contaminant pathways and contaminant control measures for those pathways. Control of contaminants for the disposal alternatives under consideration relies primarily on containment technologies and processes (to prevent or control the migration of contaminants from the sites) as opposed to treatment of the dredged material solids per se (e.g., physical, chemical, or biological treatment for destruction, enhanced degradation, or stabilization of the contaminants). For

this reason, the descriptions of the various alternatives, conceptual designs, and performance standards are closely tied to the respective contaminant pathways.

Regulatory Framework for CDF and Capping Alternatives

Proposed placement of dredged material in open water sites in Puget Sound is regulated by the USACE under Section 404 of the Clean Water Act (CWA). Section 401 of the CWA provides that states certify a proposed discharge will be in compliance with applicable state water quality standards. For the Puget Sound region, the state of Washington, the USAE District, Seattle, and EPA Region 10 have developed a regional approach for regulation of open water placement under the Puget Sound Dredged Disposal Analysis (PSDDA) program. However, there is no equivalent program for regulation of sediments to be dredged which are not suitable for disposal under the PSDDA framework, such as those considered under the MUDS framework.

The LBC and CAD alternatives evaluated under MUDS require discharge of dredged material at an open water capping site prior to placement of the cap, and such alternatives would clearly be regulated under the CWA and would require a USACE 404 permit and a 401 water quality certification from the Washington State Department of Ecology.

The regulatory framework for permitting confined (diked) alternatives also falls under the CWA. "The term 'discharge of dredged material' as defined in the CWA regulations includes, without limitation, the addition of dredged material to a specified discharge site located in waters of the United States and the runoff or overflow from a contained land or water disposal area" (33 Code of Federal Regulations (CFR) 323.2 (d) (U.S. Department of Transportation (USDOT (1984)). The policy of the USACE is that dredged material is not a solid waste (Federal Register, Vol 53, No. 80, April 26, 1988, p 14903 (USDOT 1988)).

Dredging operations of any kind, whether for purposes of navigation or environmental cleanup, require a Section 10 permit under the Rivers and Harbors Act. It is USACE policy that, regardless of how dredged material may be placed or whether there is an easily identifiable discharge to waters of the United States, the placement of dredged material in an upland dredged material disposal site is regulated under Sections 10 and 404, since Section 10 gives the USACE authority to consider all aspects of the proposed project, those related to disposal as well as the dredging activity itself.

For purposes of this section, both the upland CDF and nearshore CDF alternatives are presumed to be regulated under the Rivers and Harbors Act, and the CWA and would require a Section 10/404 permit and a 401 water quality certification.

There has been much discussion regarding the level of environmental protection afforded by the CWA regulations as compared to solid waste regulations. Regulation under Section 10 and the CWA does not preclude the need to address environmental considerations outside those directly related to water quality. Dredged material disposal activities must comply with NEPA requirements regarding identification and evaluation of alternatives. Under the National Environmental Policy Act (NEPA) framework, all facets of the dredging and discharge operation, including cost, technical feasibility, and overall environmental protection, must be considered (USACE/EPA 1992). If technical considerations require, a dredged material disposal site may be required to provide levels of environmental protection comparable to those called for under Resource Conservation and Recovery Act (RCRA) Subtitle D regulations.

Any MUDS must comply with state and local laws, regulations, and guidelines regarding design, construction, siting, and potential contaminant releases from the MUDS. Requirements potentially applicable are found in Table 1, in the following codes:

Standards for Design, Operation, and Management

Several resources are available as guidance in developing designs and site operation and management plans for dredged material disposal facilities. National technical guidance for evaluation of dredged material disposal alternatives from the environmental standpoint has been developed jointly by the USACE/EPA (1992). This "Technical Framework" describes appropriate regulatory requirements, provides a framework for alternative evaluations, and lists by reference the pertinent testing procedures and engineering and environmental evaluations which should be considered for various alternatives.

A variety of guidance documents specific to diked CDFs are available. USACE Engineer Manual (EM) 1110-2-5027 was published as a comprehensive guidance document on the engineering aspects of confined disposal design and management (Headquarters (HQ), Department of the Army (DOA) 1987). However, the EM was purposely focused on the engineering design of CDFs and does not include guidance on the environmental aspects of confined disposal, particularly those aspects related to contaminant pathway testing and assessment and design of control measures for contaminants. At the present time, guidance on the environmental aspects of CDFs, to include contaminant pathway analysis, is summarized in the USACE/EPA Technical Framework (USACE/EPA 1992) and a number of Technical Notes published by the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), Vicksburg, MS. An update of the engineer manual to include environmental aspects is now in progress.

Table 1
State of Washington Regulations Potentially Applicable to MUDS

Code	Description	Remarks
Revised Code of Washington (RCW) 90.48 Washington Administrative Code (WAC) 173-201A	State Water Pollution Control Act	Surface and groundwater quality standards that are more stringent than Federal standards
WAC 173-200	Ground Water Quality Standards	
WAC 173-204	State Sediment Quality Standards	
WAC 173-205	Whole Effluent Toxicity Testing and Limits	
RCW 90.58 WAC 173-26	State Shoreline Management	Addresses the local city or county Shoreline Master Programs and requires that a permit be obtained from the city or county
RCW 75.20.100 RCW 75.20.103	State Hydraulics Code	Includes the need to obtain Hydraulics Project Approval from the Washington State Department of Fish and Wildlife
--	Use Authorization from the Washington Department of Natural Resources if the MUDS is located on state aquatic lands.	
RCW 70.95 WAC 173-304	State Minimum Functional Standards	May be applicable to upland sites
WAC 173-340	Model Toxics Control Act (MTCA) Cleanup Regulation	
WAC 173-400	General Regulations for Air Pollution Sources	
RCW 43.21 WAC 197-11	State Environmental Policy Act (SEPA)	
WAC 173-460	Controls for New Sources of Toxic Air Pollutants	
WAC 173-470	Ambient Air Quality Standards for Particulate Matter	
WAC 173-490	Emissions Standards and Controls for Sources Emitting Volatile Organic Compounds (VOC)	
WAC 173-216	State Waste Discharge Permit Program	
WAC 173-220	National Pollutant Discharge Elimination System (NPDES)	
WAC 173-300	Solid Waste Operators Permit	
WAC 173-401	Air Quality Operating Permit.	

The USACE has also prepared guidance specific to subaqueous capping, both LBC and CAD (Palermo et al. 1998). This document expands on guidance preciously published in a series of WES technical notes on capping and describes the major design requirements for a capping project, the appropriate testing and evaluation approaches, and the sequence in which the design requirements should be considered.

Design standards for a number of confined disposal options, to include capping and CDF options, have also been developed for the Puget Sound region. The (Washington State Department of Ecology (WDOE) drafted "Standards for Confined Disposal of Contaminated Sediments," commonly referred to as the S-4 standards (Parametrix 1990). The S-4 standards include provisions for both effects-based designs and functional designs; however, the S-4 standards were never adopted as regulation(s). Functional design for upland sites must consider "Ground Water Quality Standards" (WAC 173-200) and may be subject to "Minimum Standards for Solid Waste Handling" (WAC 173-200). Functional designs (FDs) may be viewed as default designs in which specific design parameters are specified. The level of contaminant controls provided in FDs are intended for materials with relatively low levels of contaminants. Effects-based designs (EBDs) are essentially material and site-specific designs in which contaminant pathway and other testing are used as a basis of design. EBDs could be developed for a wider range of sediment contamination.

The available technical guidance in the literature, as well as available design information from projects nationwide and within Puget Sound served as the overall basis for the descriptions of disposal alternatives and features and the conceptual designs in this section. Detailed descriptions of the standards for the various alternatives under consideration are presented in the sections for each alternative.

Materials Considered for MUDS Placement

Since a MUDS disposal site or facility would be potentially used for a wide variety of projects, to include both navigation projects with levels of contamination exceeding PSDDA requirements for open water disposal and remediation projects with higher levels, it is difficult to develop a precise or typical description of the materials which may be placed in the site(s).

Since the level of contamination of materials to be placed in a MUDS facility may vary considerably, the potential for contaminant releases through the various pathways will also vary for a given site design and method of operation and management. Testing will form the basis for characterization of materials proposed for MUDS placement (see following sections), but testing will only determine acceptability of a given material. This presents several options for matching a given site design with the potential materials to be placed. One approach is to design the site to contain materials at the upper bound of sediment contamination and to control the resulting potential for pathway releases. This approach would result in a site design which would be overly conservative for

the majority of materials placed over time. Another approach is to design the site to contain materials near the lower bound of sediment contamination. This approach would potentially exclude many projects with moderate to high levels of contamination.

Figure 2 shows the relative levels of contamination as compared to various disposal site designs and the MUDS framework. At present, and for purposes of the conceptual designs in this section, it is envisioned that the MUDS alternatives would accept materials from PSDDA levels up to some level of contamination with less potential for contaminant release than those defined as dangerous waste. This concept will be refined as testing requirements under the MUDS framework are developed.

Capacity Scheduling and Frequency of Placement

The required capacity of a MUDS facility is dependent on volume of navigation dredged material deemed to be unsuitable for open water placement under the PSDDA framework and the volume of sediments likely to be generated from port development and cleanup projects in Puget Sound. Navigation dredging over the next 20 years will generate an estimated 7,600,000 cu m (10,000,000 cu yd) which may require confined disposal (U.S. Army Engineer District (USAED), Seattle (CENWS) 1995). Estimated volumes generated from cleanup range from 15,000,000 to 23,000,000 cu m (20,000,000 to 30,000,000 cu yd) (USAED, Seattle 1995). However, much of this material may go to project specific sites designed and constructed outside of the MUDS framework. Also, there is the possibility of multiple MUDS sites built contemporaneously or sequentially to meet the long-term requirements. Based on these considerations, two options for total capacity for a MUDS facility of 380,000 to 1,500,000 cu m (500,000 to 2,000,000 cu yd) are used for the conceptual designs in the following sections.

The design and operation of a dredged material disposal facility is dependent on the scheduling and frequency of dredged material placement. For example, a facility designed for a total capacity of 1,500,000 cu m (2,000,000 cu yd) over a time period of 10 years may require a deviation from the planned method of operation if a single project of 760,000 cu m (1,000,000 cu yd) must be placed in that site in a single operation. Also, the design and operation of a site in which material is placed at a slow rate on a continuous basis would be different from a site in which material is placed during short time intervals. An equal volume placed on an annual basis for 10 years is used for purposes of the conceptual designs in the following sections. This volume is assumed to be placed during the time frame to avoid seasonal dredging restrictions for Puget Sound (mid-March to mid-June). Dredging restrictions may increase in the future to protect Chinook salmon under the Endangered Species Act.

Disposal Alternative Descriptions

Descriptions of the disposal alternatives under consideration for the MUDS framework are given in the following text. The purpose of these narrative descriptions, and the more detailed information presented in the conceptual designs, is to place in proper technical perspective the need for and the basis for various design features associated with disposal alternatives and management practices. Physical, chemical, and biological processes pertaining to each alternative, such as mass balance, consolidation, resuspension, contaminant release and pathway migration, bioturbation, etc. are included. The descriptions include information on where and how the various alternatives have been implemented and considerations for implementation in the Puget Sound region.

Conceptual Designs

Conceptual designs are presented for LBC, CAD, upland CDF, and nearshore CDF alternatives in the following text. These are intended to be representative designs for each alternative developed only for purposes of preparing comparative cost estimates and potential environmental impacts. Specific design requirements or features are described for the conceptual designs, and specific design parameters and assumptions are given. However, the conceptual designs are NOT intended to be preliminary designs for any specific site, alternative, or material to be placed in a MUDS facility. Detailed site specific designs will be developed once MUDS disposal alternatives and sites have been selected. The conceptual design information can be used as part of the site selection process.

While these conceptual designs are not for a specific site, the designs do reflect conditions imposed by the Puget Sound location, e.g., the water depths, currents, waves, and ambient bathymetry found in Puget Sound. Also, the sizes of the facilities are based on the volumes of contaminated sediments expected.

Because of the intended use of the MUDS sites, the conceptual designs must consider potential contaminant control measures for a range of sediment contamination. The conceptual designs are based on representative values of pertinent site parameters such as water depths, currents, etc., representative values of sediment physical and chemical properties, and past experience in design, operation, and management of similar facilities or sites.

Once a specific alternative for MUDS is selected, a site-specific design must be developed. Any design must be based on appropriate criteria or standards. Separate standards are needed for siting and for design/performance.

Testing Requirements

The MUDS site(s) are intended to accommodate contaminated sediments from a potentially wide range of projects involving materials with comparatively low levels of contamination to those which are more highly contaminated. Several approaches may be taken to accommodate such a wide range of contamination. For example, cells or subcontainments within a given site may be designed for placement and isolation of materials with higher levels of contamination or a site could be designed for all materials. In either case, sediment testing plans must be developed to provide the necessary engineering and contaminant pathway data for each "client" project. These data would be used to determine whether and/or in what cell or site a specific sediment should be placed and/or how it should be managed. Contaminant pathways which must be considered include effluent, surface runoff, groundwater leachate, direct biological uptake and volatilization for CDF sites, and water column release and potential migration through caps for CAD sites.

No specific testing plan is presented in this programmatic stage for MUDS, but a testing plan will be developed in the site-specific stage of the MUDS evaluations. The testing plan must include development of appropriate screening approaches to determine when more expensive contaminant pathway laboratory tests are needed.

Management and Monitoring Requirements

In addition to a site-specific design, management and monitoring plans must be developed for any selected disposal alternative. These plans will be tailored to handle several contamination categories or ranges. Management plans for CAD sites should include operational aspects such as placement methods, placement locations for various tide or current conditions, limits on rate of placement, placement of interim and final caps, etc. Management plans for CDF sites should include locations of inflow points with respect to outlet structures, allowable rates of placement, management of ponded water, approaches for dewatering and consolidation to conserve capacity, final cover for site closure, etc.

Detailed plans would be developed in conjunction with site-specific designs for any disposal alternative selected during the MUDS programmatic stage. Detailed monitoring plans should include descriptions of appropriate monitoring approaches and equipment as well as generic plans for sampling locations, frequencies, etc. Conceptual monitoring requirements are outlined for each disposal alternative in subsequent sections of this report.

2 Upland Confined Disposal Facilities

Description, Definitions, and Application

Upland confined disposal is placement of dredged material within upland (diked) CDFs. CDFs are engineered structures designed to retain dredged material solids and, in the case of hydraulic dredging, to provide acceptable suspended solids and/or contaminant concentrations for discharges to receiving waters. A true upland CDF would allow for all dredged material fill to be placed above the water table. CDFs constructed in water may become upland sites once the fill reaches elevations above the mean high water elevation. Upland CDFs are not solid waste landfills. They are designed and constructed specifically for disposal of dredged material and would normally have a return flow as effluent to waters of the United States. With such return flow, they would be regulated under Section 404 of the Clean Water Act. The issue of return waters and regulation under Section 404 is a major consideration. Placement of material in upland solid waste landfills is treated as an entirely separate alternative and is not covered in this report. Upland CDFs as described in this section are assumed to meet the requirements for regulation under Section 404.

Most sediment in the Puget Sound region is dredged mechanically with bucket dredges followed by disposal in nearshore CDFs or open water. Diked sites in the Puget Sound region have been filled in many cases using mechanical means from a barge operating over a low sill dike section and were sized to accommodate a single specific dredging project volume.

In contrast, a MUDS upland CDF would likely be larger in size than most CDFs constructed in the area thus far and may be several miles from the shore. Hydraulic transport from the shore to the CDF is not a favorable option because the added water required to slurry the material increases contaminant pathway issues. For this reason, a MUDS upland CDF should accommodate mechanical offloading and transport by truck to the CDF. This process will be made more efficient by including a rehandling facility near the shore. Optional hydraulic filling methods would include hydraulic slurry from barges filled with mechanical dredges or direct pumpout from hopper dredges. Hydraulic filling methods would create more water being placed in the CDF, requiring more

expensive controls for contaminant releases from leachate and effluent, and limiting site selection to a few miles from shore.

The three objectives inherent in design and operation of CDFs are to provide for adequate storage capacity for meeting dredging requirements, to maximize efficiency in retaining the solids, and to control contaminant releases to within acceptable limits. Basic guidance for design, operation, and management of CDFs is found in EM 1110-2-5027 (HQDOA 1987).

A principal design criterion of CDFs is to retain as high a percentage of the fine-grained sediment particles as practicable. This criterion was based on the findings of the USACE Dredged Material Research Program, which demonstrated that most chemical contaminants associated with sediments could be effectively contained through efficient solids containment. Since most contaminants in sediment remain attached to solid particles during dredging and placement in the CDF, this process is reasonably efficient for containment of contaminants.

A CDF is neither a conventional wastewater treatment facility nor a conventional solid waste disposal facility. What makes it different are the physical and chemical properties of the dredged materials placed in the CDFs. Wastewater treatment facilities are designed to receive water with low levels of solids. Solid waste facilities are designed to receive solids with very little water. Dredged sediments typically contain 10 to 70 percent solids, depending on the physical characteristics of the sediment and the dredging and handling techniques used. An effective CDF must borrow features from both the wastewater treatment facility and the solid waste disposal facility in a combination that is unlike either.

The hydraulic dredging (or hydraulic reslurry) alternative generally adds several volumes of water for each volume of sediment removed, and this excess water is normally discharged as effluent from the CDF during the filling operation. The amount of water added depends on the design of the dredge, physical characteristics of the sediment, and operational factors such as pumping distance. When the dredged material is initially deposited in the CDF, it may occupy several times its original volume. The settling process is a function of time, but the sediment will eventually consolidate to its in situ volume or less, if desiccation occurs. Adequate volume must be provided during the dredging operation to contain the total volume of sediment to be dredged, accounting for any volume changes during placement.

In most cases, CDFs must be used over a period of many years, storing material dredged periodically over the design life. Long-term storage capacity of these CDFs is therefore a major factor in design and management. Once water is drained from the CDF following active disposal operations, natural drying forces begin to dewater the dredged material, adding additional storage capacity. The gains in storage capacity are therefore influenced by consolidation and drying processes and by the techniques used to manage the site both during and following active disposal operations.

Upland CDF applications

Upland CDFs are one of the most common disposal alternatives and such sites exist in most regions of the United States. The use of upland CDFs is extensive in the Atlantic and Gulf Coast regions. Many of these sites were constructed in areas adjacent to estuaries or tributary rivers near the navigation channels they were intended to serve. Some of these sites were constructed in wetland areas (prior to wetlands protection regulations) and have been filled to become upland areas. Large upland sites, some larger than 1,000 acres, are now in active use in the U.S. Army Engineer Districts, Wilmington, Charleston, Savannah, Jacksonville, Mobile, New Orleans, and Galveston. CDFs initially constructed in water and which are now upland sites are located in the Great Lakes area, California, and in Puget Sound.

Upland CDF application in Puget Sound

Use of upland CDFs has not been extensive in the Puget Sound region. Upland CDFs under the MUDS framework could be developed either as rehandling facilities where material would be temporarily managed and stored prior to removal to a landfill or other application or as final disposal sites in which material would be permanently contained. In either case, an upland CDF as described in this section is envisioned as a site within 3 km or more (2 miles) of shore-based offloading facilities from which dredged material may be mechanically rehandled directly from barges, placed in trucks or roll-off containers, transported to the CDF, and dumped from the dike of the CDF.

Contaminant Pathways

The possible migration pathways of contaminants from confined disposal facilities in the upland environment are illustrated in Figure 3. These pathways include excess water discharged during filling operations and subsequent settling and dewatering, rainfall surface runoff, leachate into groundwater, volatilization to the atmosphere, and direct uptake. Direct uptake includes plant uptake and subsequent cycling through food webs and direct uptake by animal populations living in close association with the dredged material. Effects on surface water quality, groundwater quality, air quality, plants, and animals depend on the characteristics of the dredged material, management and operation of the site during and after filling, and the proximity of the CDF to potential receptors of the contaminants. A number of control measures are available to minimize impacts of losses by these pathways. A technical framework (USACE/EPA 1992; Francingues et al. 1985) has been developed that identifies standardized testing procedures for dredged materials to determine appropriate disposal controls.

Processes and Design Considerations

There are several major considerations for design, operation, and management of upland CDFs:

a. Retaining dikes. The site conditions must allow for construction of structurally and geotechnically sound retaining dikes for effective containment of and dredged material and excess water.

b. Transport and placement of material. Upland sites may be located at some distance from the dredging areas and some distance from waterfront access. Material can be transported to an upland site using roll-off containers or by truck, but a shore-based rehandling and dewatering facility may be required. Placement by direct pipeline from hydraulic dredges would require routing a pipeline to the site.

c. Site geometry and sizing. The site must be volumetrically large enough to meet both short-term storage capacity requirements during filling operations and long-term requirements for the anticipated life of the site. Sufficient surface area and dike height with freeboard must be available for retention of fine-grained material to maintain effluent water quality .

d. Contaminant pathway controls. Provisions for control of contaminant release through any of several pathways and protection of the environment must be considered in the site design. These may include treatment of runoff or excess water prior to discharge, liners, covers, site management, or other control measures.

e. Dewatering and long-term management. Upland sites should be managed to allow for passive or active dewatering of fine-grained material. Active dewatering normally involves creating drainage trenches for removal of surface precipitation water to allow for efficient drying. Removal of dewatered material to another disposal site such as an upland landfill or removal of separated sand fractions, if clean, off site for beneficial use may also be possible.

f. Preventing releases that exceed Federal, state, and local regulations and meeting, where applicable, Minimum Functional Standards (WAC 173-300).

Each of these considerations must be appropriately addressed by the project design. More detailed discussion of these processes and design considerations is given in the following paragraphs.

Containment dikes

General. Containment dikes are retaining structures used to form confined disposal facilities. They consist primarily of earth-fill embankments. The principal objective of a dike is to retain solid particles and pond water within the disposal area while at the same time allowing the release of clarified effluent or runoff to natural waters. The location or alignment of a containment dike will usually be established by site constraints. The heights and geometric configurations of containment dikes are generally dictated by containment capacity requirements, availability of construction materials, site restrictions, and prevailing foundation conditions.

The predominant retaining structure in a containment facility extends around the outer perimeter of the containment area and is referred to as the main dike. Except as otherwise noted, all discussion in this chapter applies to the main dike. Cross and spur dikes can also be constructed to divide the site or increase site effectiveness.

The engineering design of a dike includes selection of location, height, cross section, material, and construction method. The selection of a design and construction method are dependent on project constraints, foundation conditions, material availability, and availability of construction equipment. The final choice will be a selection among feasible alternatives.

The development of an investigation for the dike foundation and for proposed borrow areas, the selection of a foundation preparation method, and the design of the embankment cross section require specialized knowledge in soil mechanics. Therefore, all designs and specifications should be prepared under the direct supervision and guidance of a geotechnical engineer. Proposed cross section designs should be analyzed for stability, since the cross section is affected by foundation and/or embankment shear strength, settlement caused by compression of the foundation and/or the embankment, seismic conditions, and external erosion. Seismic conditions should be considered as an integral part of dike design. The extent to which the site investigation(s) and design studies are carried out is dependent, in part, on the desired margin of safety against failure. This decision will usually be made by the local design agency and is affected by a number of site-specific factors.

Seismic design of containment dikes. Special considerations for design of dikes in seismically active areas, such as Puget Sound, are warranted. In general, containment dikes have performed reasonably well during past earthquakes. A commonly observed aspect is outward movement of the dike (as observed at the Oakland Airport, Loma Prieta earthquake). Outward movement or sliding can occur as a result of reduced strength in the foundation materials (liquefaction), reduced strength in the dike itself, and inadequate estimation of the loads imposed by the contained fill. A sequence of steps should be followed in evaluating ground motions and performing seismic analyses for earth and concrete and steel structures (after Krinitzsky, Hynes, and Franklin 1996, revised

by Krinitzsky 1997). These steps are provided in detail in the following sections on design and performance standards.

Transport and placement

The method selected for transfer of dredged material from dredging areas to an upland CDF is dependent on the dredging technology used in the excavation of the sediments. Direct placement of material by pipeline dredge is economical only where the site is located near the dredging areas. For most Puget Sound projects, a rehandling facility located on shore is likely to be used. With a rehandling facility, dredging can be accomplished with mechanical (bucket) dredges where the sediment is excavated at near in situ density (water content) and placed in a scow or barge for transport to the rehandling facility. Once the barge arrives, the sediment may be transferred from the barge to the CDF by several methods, depending on the distance of the CDF from point of closest access by the barge. Unloading methods include the following:

a. Clamshell the dredged material from the barge to roll-off containers or dump trucks for transport to the CDF by direct dumping or unloading into a chute or conveyor. At the CDF the dredged material will be transferred beyond the interior toe of the dike. Earthmoving equipment may be required to move material around within the CDF after dewatering.

b. Mechanically offload dredged material from a barge directly into a dewatering/rehandling facility. After dewatering, transport the material by truck or rail to the CDF or other disposal site.

c. Clamshell to a conveyor belt transferring the dredged material overland to the CDF (applicable only for relatively short distances).

d. Slurry the material in the barge by adding water and mixing, and pump the slurry through a pipeline to the CDF. (This option is not favored for the MUDS because of the distance from shore and the impact on contaminant pathways).

Initial storage capacity and solids retention

Mechanically filled CDFs are designed to retain dredged material at approximately the in situ density of the sediment in the waterway. A small amount of additional water may be added by bucket dredges, but in the Puget Sound area, evaporative drying will reduce the free water in a matter of a few weeks. A CDF must be designed and operated to provide adequate initial storage volume and surface area to hold the dredged material solids during an active filling operation. For mechanically filled sites, the design can assume no bulking, and long-term consideration and drying will reduce storage volume requirements.

A hydraulically filled site must be designed and operated to retain suspended solids such that clarified water is discharged. The required initial storage capacity, ponded water depth, and surface area are governed by settling processes which occur in a CDF during placement of fine-grained dredged material. Tests of the sediments to be dredged are required to define their behavior in a dredged material containment area. The tests provide numerical values for design criteria that can be projected to the size and design of the containment area. Procedures for computer-assisted plotting and reduction of settling column data are available. Procedures to evaluate the required surface area and volume during active filling operations, to estimate effluent suspended solids concentrations, and to design other features for CDFs are described in EM 1110-2-5027 (HQDOA 1987).

Pathway Testing and Evaluation

Upland geochemical environment

When dredged material is placed in an upland environment, physical and/or chemical changes may occur (Francingues et al. 1985). The dredged material initially is dark in color and reduced, with little oxygen. Once disposal operations are completed and any ponded water has been removed from the surface of the CDF, the exposed dredged material will become oxidized and lighter in color. The dredged material may begin to crack as it dries out. Accumulation of salts will develop on the surface of the dredged material and especially on the edge of the cracks. Rainfall events will tend to dissolve and remove these salt accumulations in surface runoff. Certain metal contaminants may become dissolved in surface runoff.

During the drying process, organic complexes become oxidized and decompose. Sulfide compounds also become oxidized to sulfate salts, and the pH may drop drastically. These chemical transformations can release complex contaminants to surface runoff, soil pore water, and leachate. In addition, plants and animals that colonize the upland site may take up and bioaccumulate these released contaminants. Volatilization of contaminants depends on the types of contaminants present in the dredged material and the mass transfer rates of the contaminants from sediment to air, water to air, and sediment to water.

Analysis of pathways for CDFs

An analysis of CDF pathways of concern must be conducted to determine if testing is warranted. Brannon et al. (1990) and USEPA/Great Lakes National Program Office (GLNPO) (1994b,c) identified key contaminant mobility processes and pathways and, where possible, methods for estimation of contaminant mass exit rates for CDFs. Pathways involving movement of large masses of water, such as CDF effluent discharge from hydraulically filled sites, have the greatest potential for moving significant quantities of contaminants out

of CDFs. Pathways such as volatilization may also result in movement of volatile organic chemicals in highly contaminated dredged sediments at certain stages in the filling of a CDF. The relative importance of contaminant cycling and mobilization of contaminants to net mass balance in a CDF has not been determined.

The USACE has developed guidelines and a framework for the Comprehensive Analysis of Migration Pathways (CAMP) for contaminated dredged material placed in CDFs (Myers 1990). CAMP has been developed as an internally consistent set of procedures for comparing the containment efficiency of CDF disposal alternatives and, as such, for providing supporting documentation for evaluating alternatives. The framework for analysis in CAMP is a tiered assessment and, as such, can be used to identify those CDF pathways which warrant more detailed assessment based on specific laboratory tests. However, CAMP is intended to interact with, but is not a substitute for, the existing effects-based dredged material test procedures presently used (Francingues et al. 1985; Lee et al. 1986). Additional discussion of the respective CDF pathways including appropriate testing protocols are given in the following paragraphs.

Effluent discharge

There should be no effluent discharge from a mechanically filled CDF. In the event of hydraulic filling, effluent will the discharged from the CDF due to the settling and consolidation of the dredged material. The effluent from a hydraulically filled CDF may contain both dissolved and particulate-associated contaminants. A large portion of the total contaminant concentration is tightly bound to the particulates. Effluent from a CDF (return flow to waters of the United States) is considered a dredged material discharge under Section 404 of the CWA and is also subject to water quality certification under Section 401 State standards.

Prediction of effluent quality for hydraulically filled CDFs should be made using a modified elutriate test procedure (Palermo 1986; Palermo and Thackston 1988) that simulates the geochemical and physical processes occurring during confined disposal. This test provides information on the dissolved and particulate contaminant concentrations. The column settling test (HQDOA 1987) used for CDF design provides the effluent solids concentrations. Results of both tests can be used to predict a total concentration of contaminants in the effluent. The predicted effluent quality, with allowance for any mixing zone, can be compared directly with water quality standards. Computer programs are also available for data reduction and analysis (Schroeder and Palermo 1990; Hayes and Schroeder 1992). The modified elutriate test is not directly applicable to mechanically filled CDFs. An analysis of pore water associated with the sediment will indicate the level of dissolved contaminants initially associated with the dredged material. Subsequent contaminant releases are best approximated by leaching and surface runoff tests.

The modified elutriate test can also be used to develop the water medium for bioassays if a biological approach to evaluation of effluent quality is needed. These bioassays are conducted in a manner similar to those for open water disposal. The quality of a reference water (usually the receiving water) should be considered in test interpretation.

If effluent contaminant concentrations exceed standards, appropriate controls should be considered. Control measures available for effluent discharge include improved settling design or reduced flow to the containment area, chemical clarification or filtration to remove particulate contaminants, and removal or destruction of dissolved contaminants by more sophisticated treatment processes.

Surface runoff

Immediately after material placement in a CDF and after ponding water is decanted, the settled material may experience surface runoff. Rainfall during this initial period will likely be erosive, and runoff will contain elevated solids concentrations. Geochemically speaking, while the material is wet, the contaminant release is controlled by anaerobic conditions. Once the surface is allowed to dry, the runoff will contain a lesser concentration of solids, but the release is now controlled by aerobic conditions, and release of some dissolved contaminants may be elevated. Runoff water quality requirements will be a condition of the water quality certification or considered as part of the NEPA/SEPA process.

Presently, there is no simplified procedure for prediction of runoff quality. A soil lysimeter testing protocol (Lee and Skogerboe 1983) has been used to predict surface runoff quality with good results. The lysimeter is equipped with a rainfall simulator and can be used in the laboratory or transported to the field site. Computer programs are also available for data reduction and analysis (Schroeder, Gibson, and Dardeau 1995).

If runoff concentrations exceed standards, appropriate controls may include placement of a surface cover or cap on the site, maintenance of ponded water conditions (although this may conflict with other management goals), vegetation to stabilize the surface, treatments such as liming to raise pH, or treatment of the runoff as for effluent (Lee and Skogerboe 1987).

Leachate

Subsurface drainage from upland CDFs may reach adjacent aquifers or may enter surface waters. Fine-grained dredged material tends to form its own disposal-area liner as particles settle with percolation of water, but consolidation may require some time for this to occur. Since most contaminants potentially present in dredged material are closely adsorbed to particles, the dissolved fraction present in leachates is usually small relative to the total contaminant mass present in the dredged material.

Evaluation of the leachate quality from a CDF must include a prediction of which contaminants may be released in leachate and the relative degree of release or mass of contaminants. Procedures are available for prediction of leachate quality which have been developed specifically for application to dredged material disposal sites (Myers and Brannon 1991; Brannon, Myers, and Tardy 1994; and Myers, Brannon, Tardy, and Townsend 1996). These procedures are based on theoretical analysis and include laboratory batch and column testing.

The testing procedures only give data on leachate quality. Estimates of leachate quantity must be made by considering site-specific characteristics and groundwater hydrology. Computerized procedures such as the EPA Hydrologic Evaluation of Landfill Performance model (Schroeder et al. 1984) have also been used to estimate water balance (budget) for dredged material CDFs (Palermo et al. 1989; Francingues and Averett 1988; Aziz, Schroeder, and Myers 1994; USEPA/GLNPO 1994a,b,c).

If leachate concentrations exceed applicable criteria, controls for leachate must be considered. These may include proper site specification to minimize potential movement of water into aquifers, dewatering to reduce leachate generation, chemical modifications to retard or immobilize contaminants, physical barriers such as clay and synthetic liners, capping/vegetating the surface to reduce leachate production, or collection and treatment of the leachate.

Plant and animal uptake

Some contaminants can be bioaccumulated in plant tissue and become further available to the food chain. If the contaminants are identified in the dredged material at levels which cause a concern, then prediction of uptake is based on a plant or animal bioassay (Folsom and Lee 1985; Simmers, Rhett, and Lee 1986; Stafford 1988). Appropriate plant or animal species are grown in either a flooded or dry soil condition using the appropriate experimental procedure and laboratory or field test apparatus. Contaminant uptake is then measured by chemical analysis of the biomass (tissue). Growth, phytotoxicity, and bioaccumulation of contaminants are monitored during the growth period in the case of the plant bioassay. An index species is also grown to serve as a mechanism to extrapolate the results to allow use of other databases, such as metals uptake by agricultural food crops. This indexing procedure provides information upon which a decision can be made regarding potential for human health effects and for beneficial uses of the site or dredged material. Levels of contaminants in the biomass are compared with Federal criteria for food or forage and to ecological risk criteria and guidelines.

From the test results, appropriate management strategies can be formulated regarding where to place dredged material to minimize plant or animal uptake or how to control and manage the species on the site so that desirable species that do not take up and accumulate contaminants are allowed to colonize the site, while undesirable species are removed or eliminated.

Volatilization to air

Contaminant transport from *in situ* sediment to air is a relatively slow process, because most contaminants must first be released to the water phase prior to reaching the air. Potential for volatilization should be evaluated in accordance with regulatory requirements of the state and Federal clean air acts. Thibodeaux (1989) discusses volatilization of organic chemicals during dredging and disposal and identifies four locales where volatilization may occur (volatilization is favored in the order of conditions listed):

a. Dredged material exposed directly to air.

b. Dredging site or other water area where suspended solids are elevated.

c. Ponded CDF with a quiescent, low-suspended solids concentration.

d. Dredged material covered with vegetation.

In cases where highly contaminated sediments are disposed, airborne emissions must be considered to protect workers and others who could inhale contaminants released through this pathway.

Rate equations based on chemical vapor equilibrium concepts and transport phenomena fundamentals have been used to predict chemical flux (Thibodeaux 1989; Semmler 1990). First-generation laboratory tests for prediction of volatile losses have also been developed (Price et al. 1997). Emission rates are primarily dependent on the chemical concentration at the source, the surface area of the source, and the degree to which the dredged material is in direct contact with the air.

CDF Operation and Management

Placement of weirs and inflow points

Outflow weirs are usually placed on the site perimeter at the point of lowest elevation. The material offloading areas or the dredge pipe inlet is usually located as far away as practicable from these outflow weirs. However, these objectives may sometimes be conflicting. If the disposal area is large or if it has irregular foundation topography, considerable difficulty may be encountered in properly distributing the material throughout the area and obtaining the surface elevation gradients necessary for implementation of a surface trenching program. One alternative is to use interior or cross dikes to subdivide the area and thus change the large area into several smaller areas. Effective operation may require that the inlet/offloading location be moved periodically from one part of the site to another, to ensure a proper filling sequence and obtain proper surface elevation gradients. Also, shifting inflow from one point of the site to another and

changing outflow weir location may facilitate obtaining a proper suspended solids concentration in disposal site effluent or rainfall runoff.

Installation and operation of multiple outflow weirs

In conjunction with provisions for moving the inflow point over the disposal site, it may also be worthwhile to contemplate installation of more outflow weirs than would be strictly required by design methods. Availability of more outflow points allows greater flexibility in site operation and subsequent drainage for dewatering, as well as greater freedom in movement of dredge inflow points while still maintaining the flow distances required to obtain satisfactory suspended solids concentrations in disposal site effluent. Also, a higher degree of flexibility in both disposal site inflow and outflow control will allow operation of the area in such a manner that desired surface topography can be produced, facilitating future surface trenching operations.

Interior dike construction

The basic rationale behind the construction of interior disposal area dikes is to subdivide the area into more manageable segments and/or to control the flow of dredged material through the disposal area. Control of material placement is normally to facilitate future disposal site operations, such as dewatering, or to provide proper control of disposal area effluent. Interior dikes may also be used as a haul road and access for movement of material for dike construction or other beneficial uses. Interior dikes may also serve to divide the site into cells with different levels of containment such as liners or slurry walls.

As a general rule, the use of interior cross dikes in any disposal area will increase the initial cost of construction and may result in increased operating costs. However, facilitation of disposal site operations, particularly future dewatering, may result in a general reduction in unit disposal cost over the life of the site. The benefit derived from dikes should be evaluated against the amount of disposal volume required for their construction. If the dikes can be constructed from dredged material or material available in the disposal site foundation and subsequently raised with dewatered dredged material, the net decrease in storage capacity will be approximately zero.

Surface water management

The management of surface water during the disposal operation can be accomplished by controlling the elevation of the outlet weir(s) throughout the disposal operation. A mechanically filled CDF will generate a minimum volume of excess water compared to a hydraulically filled site. This water can normally be contained within the site during filling. After active filling is completed, free water, not already removed by evaporation, may be drained from the site through the adjustable weirs.

At the beginning of a hydraulic disposal operation, the outlet weir is set at a predetermined elevation to ensure that the ponded water will be deep enough for settling as the containment area is being filled. As the disposal operation begins, slurry is pumped into the area; no effluent is released until the water level reaches the weir crest elevation. Effluent is then released from the area at about the same rate as slurry is pumped into the area. Thereafter, the ponding depth decreases as the thickness of the dredged material deposit increases. After completion of the disposal operation and the activities requiring ponded water, the water is removed as quickly as effluent water quality standards will allow.

Post dredging management activities

Periodic site inspections and continuous site management following the dredging operation are desirable. Once the dredging operation has been completed and the ponded water has been decanted, site management efforts should be concentrated on maximizing the containment storage capacity gained from continued drying and consolidation of dredged material and foundation soils. To ensure that precipitation does not pond water, the weir crest elevation must be kept at levels allowing efficient release of runoff water. This will require periodic lowering of the weir crest elevation as the dredged material surface settles.

Removal of ponded water will expose the dredged material surface to evaporation and promote the formation of a dried surface crust. Some erosion of the newly exposed dredged material may be inevitable during storm events; however, erosion will be minimized once the dried crust begins to form within the containment area.

Natural processes often need man-made assistance to effectively dewater dredged material, since dewatering is greatly influenced by climate and is relatively slow. When natural dewatering is not acceptable for one reason or another, then additional dewatering techniques should be considered. These techniques include trenching, vertical strip drains, and subsurface drainage to enhance drainage of water from saturated material beneath the crust.

Removal of coarse-grained material for productive off-site use by employing Disposal Area Reuse Management (DARM) techniques will further add to capacity. Dewatered fine-grained material may also be used for dike maintenance or raising. This concept has been successfully used by CE Districts and demonstrated in field studies. Guidelines for determining potential benefits through DARM are found in Technical Report DS-78-12 (USAEWES 1978). Additional information on productive uses of dredged material is found in EM 1110-2-5025 (HQDOA 1987).

Contaminant Control Measures for CDFs

In cases where evaluations of direct physical impacts, site capacity, or contaminant pathways indicate impacts will be unacceptable when conventional CDF disposal techniques are used, management actions and contaminant control measures may be considered. Descriptions of the commonly used management actions and contaminant controls are given in the following paragraphs. Additional guidance on selection of management actions and contaminant controls for CDFs is available (HQDOA 1987; Francingues et al. 1985; Cullinane et al. 1986; Averett et al. 1990; USEPA/GLNPO 1994a,b,c). These references contain testing procedures and criteria needed for evaluating and selecting appropriate contaminant control measures for CDFs and should be consulted for additional detailed discussions of the attributes of the various technologies.

Treatment of Discharges to Surface Water

The objective of liquid streams controls is to remove residual contaminants from the liquids produced as discharges from a CDF operation such as:

a. Surface runoff.

b. Leachate.

c. Waters from dewatering or treatment processes.

d. Effluent discharges from active hydraulic filling operations.

Contaminants in these streams will present a wide array of concentrations depending on their source, and individual sources are often highly variable in concentrations and flows. Most of the contaminants for these streams are associated with the suspended solids and will be removed by effective suspended solids removal. Another characteristic of these streams is their variety of contaminants, both organic and inorganic, at potentially toxic concentrations. These characteristics may require more than one treatment process. Commonly used wastewater treatment processes are available to achieve effluent limits for most contaminants. However, applications of treatment processes for dredged material effluents have been generally limited to removal of suspended solids and contaminants associated with these particulates.

Liquid treatment technologies beyond suspended solids removal can be classified as metals removal processes or organic treatment processes. Many of these processes, such as carbon adsorption or precipitation, concentrate contaminants into another phase, which may require special treatment or disposal. Conventional contaminants, such as nutrients, ammonia, oxygen-demanding materials, and oil and grease, may also be a concern for dredged material

effluents. Many of the processes for dissolved organics removal are suitable for these contaminants.

Suspended solids removal

Suspended solids removal is the most important liquid streams technology because it offers the greatest benefits in improving effluent quality not only by reducing turbidity but by removing particulate-associated contaminants. Suspended solids removal processes differ from dewatering processes, because for this application the solids concentration is much lower than for a dredged material slurry. Settling mechanisms for these streams are characterized by flocculent settling rather than zone or compression settling. For CDF liquid streams, the solids remaining will be clay or colloidal size material that may require flocculants to promote further settling in clarifiers or sedimentation ponds. Chemical clarification using organic polyelectrolytes is a proven technology for CDF effluents (Schroeder 1983; Schroeder and Shields 1983). Filtration, permeable dikes, sand-filled weirs, and wetlands have also been used on occasion for CDF demonstrations or pilot evaluations. More detailed guidance on suspended solids removal processes as applied to CDFs is available (HQDOA 1987; Cullinane et al. 1986; USEPA/GLNPO 1994a,b,c).

Metals removal

Metals removal processes that may be considered for application at CDFs are similar to those commonly used for industrial applications. Processes that are developmental and less likely choices are biological ion exchange, electrocoagulation, and ultrafiltration. Flocculation is effective for removal of metals associated with particulate matter. Polymers and inorganic flocculants have been demonstrated to be effective for removal of suspended solids from dredging effluents, but removal of dissolved heavy metals has not been evaluated in field applications. Ion exchange and precipitation are probably two of the more efficient metals removal processes, but they must generally be designed for specific metals and often require major investments in operational control for efficient operation. Use of man-made wetlands is a relatively new concept for retention of heavy metals and other contaminants from effluents, which could represent a viable option for certain sites and contaminants (Fennessy and Mitsch 1989). More detailed guidance on metals treatment processes as applied to CDFs is available (Cullinane *et al.* 1986; Averett *et al.* 1990; USEPA/GLNPO 1994a,b,c).

Organics treatment

The applicability and effectiveness of options for treatment of dissolved organic contaminants are mostly dependent on the concentration and flow rate of the liquid stream. Mechanical biological wastewater treatment processes are typically not considered because it is doubtful that sufficient organic matter

would be available to support biological growth and because operation of biological systems under the conditions of fluctuating flows and temperatures would be difficult. Biological processes such as nitrification, nutrient catabolism, and photosynthesis are important degradation mechanisms for nutrients, oxygen-demanding materials, and other organics in CDFs. The principal process for dissolved refractory organic contaminants that has been applied to dredged material effluent is carbon adsorption, which was applied to a polychlorinated biphenyl (PCB) spill on the Duwamish Waterway in the 1970's (Blazevich et al. 1977). Air and steam stripping could be used for volatile contaminants, but these are generally not a problem for contaminants originating in most dredged sediments. Ultraviolet light (UV) and chemical oxidation processes offer destruction of organic contaminants and are being extensively investigated in the field for a wide range of contaminants. UV and hydrogen peroxide treatment were used for dredged material effluent from the New Bedford Harbor Superfund site (Otis 1994). Created wetlands or phytoremediation also offer potential for retention and degradation of organics. The more effective organic treatment process options are:

a. Carbon adsorption.

b. Chemical oxidation processes.

c. Oil separation.

d. Wetlands/phytoremediation.

More detailed guidance on organics treatment processes as applied to CDFs is available (Cullinane et al. 1986; Averett et al. 1990; USEPA/GLNPO 1994a,b,c).

Site controls

Site controls (e.g., surface covers and liners) can be effective control measures applied at a CDF to prevent migration of contaminants from the dredged material (Cullinane et al. 1986; Averett et al. 1990). The implementability and effectiveness of these controls is highly specific to the CDF location and the dredged material characteristics.

Use of site controls such as liners, slurry walls, groundwater pumping, and subsurface drainage can be considered for upland sites. Graded stone dikes with low-permeability cores or steel sheet-pile cutoffs have been used or proposed at upland CDFs to control leachate migration. The low permeability of fine-grained sediments following compaction can reduce the need for liners in many cases, but it can also limit the effectiveness and implementability of groundwater pumping and subsurface drainage controls.

A cover can be highly effective in reducing leachate generation by avoiding rainfall infiltration, isolation from bioturbation and uptake by plants and animals, minimizing volatilization of contaminants from the surface, and eliminating

detachment and transport of contaminants by rainfall and runoff. A layer of clean material can achieve the last three benefits mentioned. However, prevention of infiltration requires a barrier of very low permeability, such as a flexible membrane or a compacted clay layer, both of which are not easily or reliably implemented for CDFs. Other leachate control measures include groundwater pumping, liners, subsurface drainage, sheet-pile walls, slurry walls, and surface drainage. Liners have not been used extensively for contaminated dredged material sites because of the inherent low permeability of fine-grained dredged material, the retention of contaminants on solids, and the difficulty and expense of construction of a reliable liner system for wet dredged material. Leachate collection techniques, such as groundwater pumping and subsurface drainage, have been evaluated in a limited number of situations. Sheet-pile walls and slurry walls can be used to provide barriers to leachate and seepage movement from a CDF. To be effective, the barrier should tie to a geologic formation with very low permeability. Sheet-pile walls are not leakproof and deteriorate over time; therefore, they should not be considered as a primary containment measure. More detailed guidance on site controls for CDFs is available (Cullinane et al. 1986; Averett et al. 1990).

Treatment of Dredged Material Solids

Various treatment processes have been investigated for dredged material treatment. Treatment of contaminated dredged material is a multistep process as shown in Figure 4. All steps of the process (that is, the process train) must be considered when planning and designing treatment options for contaminated dredged material. These steps are:

a. Removal or dredging of sediment.

b. Transport of dredged material.

c. Pretreatment of dredged material.

d. Treatment of dredged material.

e. Disposal of dredged materials.

f. Water (effluent and leachate) treatment.

Steps *a*, *b*, and *e*, and sometimes step *f*, are required for CDF alternatives. All steps are required for alternatives that include treatment.

The technology types that may be considered for each component are listed in Table 2. A variety of process options are potentially available for each type of technology; however, prior to recent demonstration programs and Superfund cleanups, only a limited number of treatment technologies had actually been applied on a pilot scale or full scale. The base of experience for treatment of contaminated sediment is still very limited.

Table 2
Treatment Technologies for Contaminated Dredged Material

Pretreatment	Treatment	Effluent Treatment
Dewatering • Settling pond • Belt filter • Chamber filter • Thickener • Centrifuge **Particle classification** • Flotation • Grizzlies • Hydrosizer • Hydrocyclones • Screens • Spiral classification • Shaking tables • Magnetic separation • Electrostatic • Settling basin • Attrition scrubbing **Slurry injection** • Chemical clarification • Nutrients/microbes	**Biological** • Bioslurry • Contained land • Land farming • Composting **Chemical** • Oxidation • Reduction • Dechlorination **Extraction** • Organic solvents • Acids/chelates • Supercritical • Surfactants • Electrokinetics **Immobilization** • Solidification • Stabilization • Vitrification • Sorption **Thermal** • Incineration • Desorption • Pyrolysis • Sintering	**SS removal** • Settling • Flocculation • Granular media filter • Membrane filter • Wetlands **Metals removal** • Precipitation • Ion exchange • Adsorption • Mixed media filters • Wetlands **Organic treatment** • Carbon/resin adsorption • Oxidation • Biofilters • Wetlands • Oil separation

Pretreatment component

Pretreatment technologies are defined as technologies that prepare or condition dredged material for subsequent, more rigorous treatment processes. These technologies are designed to accelerate treatment, to reduce the water content of the dredged material, or to separate fractions of the sediment by particle size. Pretreatment technology process options include dewatering, debris removal, particle separation or classification, and slurry injection of polymers, nutrients, or other materials in preparation for treatment. For any contaminated sediment project, most treatment technologies will require storage for flow equalization between the dredging step and the treatment step. A diked storage area similar to a CDF serves this purpose, as well as allowing for dewatering and removal of debris, cobbles, and other large materials.

Treatment component

Many of the process options are not stand-alone processes but are components of a system that may involve multiple treatment processes to address multiple contaminant problems. Most of these processes also require one or more of the pretreatment processes discussed above. Technology types for the treatment component are listed in the following text:

a. Biological.

b. Chemical.

c. Extraction.

d. Immobilization.

e. Thermal destruction.

f. Radiant energy.

Biological processes. Biological degradation technologies use bacteria, fungi, or enzymes to break down PCBs, pesticides, and other organic constituents into innocuous or less toxic compounds. The microorganisms may be indigenous microbes, conventional mutants, or recombinant DNA products. Biodegradation processes have been widely evaluated for contaminated soils and sediments on bench and pilot scales. However, few full-scale cleanups have been completed for the more difficult to degrade compounds such as PCBs, dioxins, and high molecular weight polynuclear aromatic hydrocarbons (PAHs). Several of the conceptual processes are proprietary processes that may be available on a pilot scale, and new vendors continue to enter this market. Bioslurry processes are estimated to cost $80 to $200/cubic meter (cubic yard). A potentially lower cost would be incurred if biodegradation can be conducted in a CDF. Research being conducted at ERDC and elsewhere seeks to develop techniques for CDF management that will affect biotreatment.

Chemical processes. Chemical treatment technologies use chelating agents, bond cleavage, acid or base addition, chlorine displacement, oxidation, or reduction in the destruction or detoxification of contaminants found in the contaminated media. The most widely applied chemical technology is dechlorination of PCBs and other chlorinated aromatic compounds. Process options include the potassium polyethylene glycol process, the base catalyzed dechlorination process, the alkaline metal hydroxide/polyethylene glycol process, and the potassium glyme methoxy ethanol (KGME) process (which uses the potassium derivative of 2-methoxyethanol (glyme)). These processes have been demonstrated on bench and pilot scales and have been used for full-scale cleanup of some small contaminated soil sites. Implementation of chemical processes is difficult because of materials handling and process control requirements that have not been fully demonstrated for application to dredged material. Costs for these processes range from $100 to $300/cubic meter (cubic yard).

Extraction processes. Extraction is the removal of contaminants from a medium by dissolution in a fluid that is later recovered and recycled in the process or treated. Soil flushing and soil washing are other terms that are used to describe extraction processes, primarily when water is a component of the solvent. A key element of an extraction process is the ability to separate the contaminant from the solvent so that the solvent can be recovered for reuse in the

process. Also important is the toxicity of the solvent. Most processes require multiple extraction cycles to achieve high removal efficiencies. Follow-on treatment processes are required to treat or dispose of the concentrated contaminant stream. Implementation of most of these processes is difficult because of the lack of full-scale development for handling sediment and the problems of solvent recovery and potential toxicity of residual solvents. Costs are expected to exceed $150 to $400/cubic meter (cubic yard).

Immobilization processes. Immobilization processes are defined as technologies that limit the mobility of contaminants for sediment placed in a confined site or disposal area. The environmental pathway most affected by these processes is transport of contaminants to the groundwater or surface water by leaching. Most of the immobilization processes fall into the category of solidification/stabilization (S/S) processes. Objectives of S/S are generally to improve the handling and physical characteristics of the material, decrease the surface area of the sediment mass across which transfer or loss of contaminants can occur, and limit the solubility of contaminants by pH adjustment or sorption phenomena.

The effectiveness of S/S processes is usually evaluated in terms of reduction of leaching potential. Reductions are process- and contaminant-specific, with immobilization of some contaminants accompanied by increased mobility of other contaminants. Implementation of most of these processes is better than chemical or extraction processes because they are not as sensitive to process control conditions. The opportunity for *in situ* S/S within a CDF is also an advantage. Costs for these processes are generally less than $100/cubic meter (cubic yard). S/S of dredged material is currently being practiced for two dredged material projects in New York Harbor. The stabilized material is being used for construction fill.

Thermal processes. Thermal technologies include incineration, pyrolysis, thermal desorption, sintering, and other processes that require heating the sediment to several hundreds or thousands of degrees above ambient. Thermal destruction processes such as incineration are generally the more effective options for destroying organic contaminants, but they are also the more expensive. Thermal desorption could be considered an extraction process since the organic contaminants are removed from the sediment by volatilization. The small volume of volatilized contaminants must be collected for subsequent treatment. Costs for thermal processes range from $100 to $400/cubic meter (cubic yard) for desorption processes, to more than $1,000/cubic meter (cubic yard) for the more energy-intensive processes such as incineration.

Radiant energy processes. These processes incorporate photodegradation technologies to destroy organic contaminants. X-ray treatment and ultraviolet light have been investigated on laboratory and pilot scales, but they should be considered technologies not yet ready for full-scale demonstration.

Treatment technology demonstrations

Some of these treatment processes have been applied in pilot-scale demonstrations, and some have been applied in full-scale demos. Examples of the field evaluation of various process options for the above technology types are presented in Table 3. The USEPA Assessment and Remediation of Contaminated Sediments Program, the Canadian Great Lakes Cleanup Fund, and the New York Harbor Sediment Decontamination Program have investigated treatment technologies on bench- and pilot-scale levels. The relatively high cost of such treatment alternatives is a major constraint on their potential use, and they have not been used for maintenance dredging projects. A recent report by the Marine Board National Research Council (1997) concluded that "..because of extraordinarily high unit costs, thermal and chemical destruction techniques do not appear to be near-term, cost-effective approaches for the remediation of large volumes of contaminated dredged sediment." An international group recently completed a report on "Handling and Treatment of Contaminated Dredged material from Ports and Inland Waterways" (PIANC 1996). With respect to treatment, this report concluded "Landfarming, bioslurry treatment, flotation, and gravitational separation are very promising" and "the costs of treatment are still high, but are decreasing." Treatment technologies have been used for Superfund Cleanup Projects at Bayou Bonfouca, New Bedford Harbor, Marathon Battery, and Waukegan Harbor. Costs for these projects ranged from $100 to $1,000 per cubic meter (cubic yard).

Site operations

Site operations can be used as a control measure for CDFs to reduce the exposure of material through the surface water, volatilization, and groundwater pathways. Operational controls may include management of the site pond during and after disposal operations. Mobilization of contaminants from dredged material depends on the oxidation state of the solids. Most metals are much less mobile when maintained in an anaerobic reduced condition. On the other hand, aerobic sediments generally improve conditions for biodegradation of organic contaminants. Aerobic sediments generally present the greatest potential for volatilization of contaminants (Thibodeaux 1989). Whether to cultivate or inhibit plant and animal propagation is also an issue. Management of the site both during filling and after disposal requires a comprehensive understanding of the migration pathways and the effects various contaminant controls have on the overall mass balance and rate of contaminant releases. The decision to apply certain management options requires trade-offs for the site and contaminant-specific conditions for the project.

Table 3
Sediment Treatment Examples (Averett and Francingues 1994)

Country/Location	Project Type	Contaminants	Process Options	Scale
		BIOLOGICAL		
USA/WI Sheboygan R.	Remedial (Superfund)	PCBs	Contained land	Pilot
Canada/ON Hamilton H.	Remedial CSTTP[1]	PAHs	Contained land	Pilot
Canada/ON Toronto H.	Remedial CSTTP	PAHs	Bioslurry	Pilot
Netherlands Zeeland	Navigation DPTP[2]	PAHs	Land farming	Pilot
		CHEMICAL		
Canada/ON Hamilton H.	Remedial CSTTP	PAHs	Reduction(thermal w/hydrogen)	Pilot
Netherlands Elburg	Navigation DPTP	PAHs	Wet oxidation	Pilot
		EXTRACTION		
USA/IN Gr. Calumet	Remedial ARCS[3]/ SITE[4]	PCBs, PAHs	Triethyl amine solvent	Pilot
USA/MA New Bedford	Remedial SITE	PCBs	Supercritical propane	Pilot
Canada/ON Toronto H.	Remedial CSTTP	Metals	Acid extraction Chelation	Pilot
		IMMOBILIZATION		
USA/NY Marathon Bat	Remedial Superfund	Metals Cd, Ni	Stabilization	Full
Belgium Vilvoorde		Metals	Solidification	Full
USA/NY Buffalo R.	Remedial ARCS	Metals	Solidification (post thermal desorption)	Pilot
		THERMAL		
USA/LA Bayou Bonfouca	Remedial Superfund	Creosote PAHs	Incineration	Full
USA/IL Waukegan	Remedial Superfund	PCBs	Thermal desorption	Full

(Continued)

[1] Contaminated Sediment Treatment Technology Program, Environmental Canada.
[2] Development ProgramTreatment Processes, The Netherlands.
[3] Assessment and Remediation of Contaminated Sediments Program, United States.
[4] Superfund Innovative Technology Evaluation Program, United States.

Table 3 (Concluded)				
Country/Location	**Project Type**	**Contaminants**	**Process Options**	**Scale**
		THERMAL (concluded)		
USA/OH Ashtabula	Remedial ARCS	PCBs	Thermal desorption	Pilot
USA/NY Buffalo R.	Remedial ARCS	PAHs	Thermal desorption	Pilot
Netherlands Elburg	Remedial	Metals	Sintering	Pilot
		PARTICLE SEPARATION		
USA/MI Saginaw R.	Remedial ARCS	PCBs Metals	Screens, Hydrocyclones	Pilot
Canada/ON Toronto	Remedial CSTTP	Metals PAHs	Attrition scrubbers Hydrocyclones	Pilot
Germany Hamburg	Navigation	Metals PAHs, PCBs	Screens, Hydrocy-clones, Belt filt.	Full
Canada/ON Welland	Remediation CSTTP	Metals	Screens, Screw class., Centrifg.	Pilot
Netherlands Rotterdam	Remediation	Metals PAHs	Hydrocyclones Settling basins	Pilot

Dewatering and Long-Term Storage

Factors affecting long-term storage capacity

Long-term storage capacity should be considered for an upland CDF intended for long-term use (Palermo 1992). Consolidation and desiccation are long-term processes which will affect the long-term storage capacity.

The coarse-grained fraction of dredged material (sands and coarser material) undergoes sedimentation quickly and will occupy essentially the same volume as occupied prior to dredging. However, the fine-grained fractions of the material (silts and clays) require longer settling times, initially occupy considerably more volume than prior to dredging, and will undergo a considerable degree of long-term volume change due to consolidation if hydraulically placed. Such materials are essentially under-consolidated soils, and the consolidation takes place due to self-weight loading.

Dredged material placement also imposes a loading on the containment area foundation, and additional settlement may result from consolidation of compressible foundation soils. Settlement resulting from consolidation is therefore a major factor in the estimation of long-term storage capacity. Since the consolidation process for fine-grained materials is slow, total settlement may not

have taken place before the containment area is required for additional placement of dredged material. Settlement of the containing dikes may also significantly affect the available storage capacity and should be carefully considered.

Once a given active filling operation ends, any ponded surface water required for settling should be decanted, exposing the dredged material surface to desiccation (evaporative drying). This process can further add to long-term storage capacity and is a time-dependent and climate-dependent process. However, active dewatering operations such as surface trenching enhance the natural dewatering process.

Desiccation of dredged material is basically removal of water by evaporation and transpiration. Plant transpiration can also enhance dewatering but is not considered in this chapter. Evaporation potential is controlled by such variables as radiation heating from the sun, convective heating from the earth, air temperature, ground temperature, relative humidity, and wind speed. However, other factors affect actual evaporative drying rates. For instance, the evaporation efficiency is normally not a constant but some function of depth to which the layer has been desiccated and also is dependent on the amount of water available for evaporation.

Methods are readily available to predict the capacity gains possible through consolidation and desiccation. The data required to estimate long-term storage capacity include physical properties of the sediments and foundation soils such as specific gravity, grain size distributions, Atterberg liquid and plastic limits, and water contents; the consolidation properties of the fine-grained dredged material and foundation soils (relationships of void ratio and permeability versus effective stress); CDF site characteristics such as surface area, ultimate dike height, groundwater table elevations, average pan evaporation rates, average rainfall; and dredging data such as volumes to be dredged, rate of filling, and frequency of dredging (HQDOA 1987 and Stark 1991).

Dredged material dewatering operations

If the CDF is well-managed following active filling, the excess water will be drained from the surface and natural evaporation will act to dewater the material. However, active dewatering operations should be considered to speed up the dewatering process and achieve the maximum possible volume reduction, considering the site-specific conditions and operational constraints.

Dewatering results in several benefits. Shrinkage and additional consolidation of the material resulting from dewatering operations leads to creation of more volume in the CDF for additional dredged material. The drying process changes the dredged material into a more stable soil form amenable to removal. Dewatered material remaining in the CDF forms a more stable fast land with predictable geotechnical properties. Also, the drainage associated with dewatering helps control mosquito breeding.

A number of dewatering techniques for fine-grained dredged material have been studied (Haliburton 1978; Haliburton et al. 1991). However, surface trenching and use of underdrains were found to be the only technically feasible and economically justifiable dewatering techniques (Haliburton 1978). Techniques such as vacuum filtration or belt filter presses can be technically effective but are not economical for dewatering large volumes of fine-grained material.

The concept of surface trenching to dewater fine-grained dredged material was first applied by the Dutch (d'Angremond et al. 1978), and later field-verified under conditions typical of CDFs in the United States (Palermo 1977). Surface trenching has since become a commonly used management approach for dewatering in CDFs (Poindexter 1988, Poindexter-Rollings 1989).

Construction of trenches around the inside perimeter of confined disposal sites using draglines as shown in Figure 5 is a procedure that has been used for many years to dewater and/or reclaim fine-grained dredged material. In many instances, the purpose of dewatering has been to obtain convenient borrow material, if not contaminated, to raise perimeter dikes. Draglines and backhoes are adaptable to certain perimeter trenching activities because of their relatively long boom length and/or method of operation and control. The perimeter trenching scheme should be planned carefully so as not to interfere with operations necessary for later dewatering or other management activities.

The low-ground-pressure chassis may be tracked or rubber-tired, as shown in Figures 6 and 7.

A suggested scheme for perimeter and interior trenching using a combination of draglines and a rotary trencher or other suitable equipment and incorporating both radial and parallel trenches is shown in Figure 8.

Monitoring

A monitoring program must be developed to comply with regulatory requirements and to operate the CDF effectively. Monitoring could include evaluation of all of the environmental pathways (surface water, groundwater, plant and animal uptake, and air) identified as being important. Most CDF monitoring programs are limited to sampling for effluent suspended solids and maintaining good records for the volumes and types of materials placed in the facility. Effluent monitoring will be required during filling and may be required for rainfall runoff, while contaminated material is exposed, i.e., prior to capping with clean material. Chemical analysis of effluent quality may be necessary for highly contaminated sediment. The parameters analyzed should target contaminants of concern that are present in the sediment.

Leachate monitoring also may be required for highly contaminated material where groundwater contamination is an issue. Leachate monitoring requires the installation of monitoring wells for sampling of leachate and/or groundwater and

subsequent chemical analyses. Where CDFs become a haven for wildlife, monitoring of contaminant uptake in the food chain may be a consideration. Monitoring of leachate effects and plant and animal uptake would involve long-term commitments to monitor the site.

Air emissions have seldom been monitored for CDFs; however, air monitoring may be considered where extremely high concentrations of organic contaminants are present in the dredged material and where there is a high likelihood of human receptors. Air monitoring was practiced at the New Bedford Harbor Superfund Site during dredging of PCB sediments containing PCB concentrations in the range of 4,000 to 100,000 mg/kg (Otis 1994). This was obviously an extreme case not likely to be encountered in a Puget Sound MUDS site.

Conceptual Design for Upland CDF/ Rehandling Facility

Two options are presented for the conceptual design for the upland CDF. The first option assumes that an upland CDF would be constructed as a disposal site to contain dredged material placed over a 10-year time frame. The second option assumes that an upland rehandling/ dewatering facility would be constructed which would facilitate temporary storage and pretreatment in the form of dewatering. Materials would be periodically removed from such a facility and transported to an upland landfill or CDF or to beneficial use.

Overview

The conceptual design for the upland CDF was developed for two storage capacities, 150,000 cu m (200,000 cu yd) of material each year for a 10-year period, for a total of 1,500,000 cu m (2,000,000 cu yd) as measured prior to dredging and 38,000 cu m (50,000 cu yd) of material each year for a 10-year period for a total of 380,000 cu m (500,000 cu yd). The site for the 1,500,000 cu m (2,000,000 cu yd) of dredged material would occupy an area of approximately 650,000 sq m (160 acres) with a final 2.4-m (8-ft) thickness of sediment. The site for the 380,000 cu m (500,000 cu yd) of dredged material would occupy an area of approximately 160,000 sq m (40 acres) with a final 2.4-m (8-ft) thickness of sediment. These volumes consider no reduction as a result of dewatering and desiccation over the long term. The overall dimensions and configuration for the upland CDF conceptual design to contain the 1,500,000 cu m (2,000,000 cu yd) of dredged material are shown in Figure 9.

The first alternative for the upland CDF would be divided into three cells to improve management of the dredged material disposal as shown in Figure 10. One cell would be lined and contain a leachate collection system to accommodate more highly contaminated sediment. Cleaner dredged material would be

placed in the unlined CDF cells. The decision for which cell to use will be based on pathway testing and regulatory reviews. A cross section of the lined cell is shown in Figure 11.

The dredged material would be loaded onto barges and shipped to the barge offloading facility. The dredged material could then be placed directly into a truck or a railcar for transport to the CDF. Hydraulic placement of the dredged material into the CDF could also be used for transport of the material.

In the event that the hydraulic placement is used for the dredged material, then outflow structures would be placed in the dikes to remove excess water from the dredged material. These outflow structures would consist of a weir and filter cells. Either the weir or the filter cells could be used to remove the water from the cell depending on the concentration of suspended solids entering the secondary basin and filter cells. If the water met discharge requirements, then the weir could be used to remove the water to a drain for transport to appropriate waters regulated under Section 404. If the water did not meet discharge requirements, then the filter cells could be used to remove the suspended solids for discharge. A minimum of two filter cells should be included in the design. This allows for using one filter cell while the other one is being recharged in the event of plugging of the filter.

Contaminant control measures assumed for the conceptual design include a bottom liner and leachate collection system for one subcontainment and a surface cover of clean material over the entire site upon closure.

Containment Dikes

The conceptual design for the upland containment dikes is based on a review of CDF dike designs nationwide and the required capacity for this MUDS alternative. The total volume requirement was reduced for sizing the site using a long-term volume ratio of 0.75, allowing for the dewatering and consolidation of the dredged material. This ratio is considered conservative in that ratios of 0.5 have been achieved in sites along the Atlantic seaboard and Gulf Coast. Allowing for the climate conditions typical of the Puget Sound region, less efficient dewatering would be expected. The total volume of fill at the end of the 10-year placement period is therefore 1,100,000 cu m (1.5 million cu yd) for the designed 1,500,000-cu m (2,000,000-cu yd) facility and 290,000 cu m (375,000 cu yd) for the 380,000-cu m (500,000-cu yd) designed facility. Assuming an average depth of 2.4 m (8 ft) for the dredged material fill, the dikes would be approximately 3.7 m (12 ft) in height. This allows for 0.61 m (2 ft) of free board and room for placement of 0.61 m (2 ft) of clean cover material for closure. Although an increased depth of dredged material would decrease surface area for the same volume, dewatering the thicker depth would take more time.

The dike material is assumed to be constructed from onsite soils and could be characterized as clean fill. The material would be placed and compacted to optimum density. Side slopes of 3:1 are assumed for the construction of the

main dikes. The top of the dike would be 6 m (20 ft) across to accommodate the movement of machinery around the site for dike inspection and maintenance and to allow for offloading the trucks. For purposes of the conceptual design, these dimensions are assumed to meet required safety factors for stability under both static and seismic loadings.

The overall length of the main dike for the upland CDF is approximately 3,400 m (11,200 ft) for the 1,500,000-cu m (2,000,000-cu yd) CDF and 1,042 m (3,420 ft) for the 380,000-cu m (500,000-cu yd) CDF . This dike could be built in a rectangular shape as indicated in Figure 9. Site-specific design could dictate changes in the site geometry. Cross dikes would be constructed to divide the CDF into three cells, one of which would be lined to accept contaminated material.

Transport and Placement

The method for transporting dredged material to the upland CDF is assumed to be by barge to offloading facilities. The dredged material will be placed in barges by clamshell and shipped to the barge offloading facility. The dredged material will be offloaded into trucks or rail cars for transport to the upland CDF.

Operation and Management

The surface area required for the total storage of the dredged material is assumed to be adequate for the primary settling of the material. The total volume of the site is assumed to be adequate for the initial storage (bulking) during each placement of dredged material in the CDF and for clarification efficiency (removal of suspended solids from excess water or from surface runoff).

Contaminant Control Measures

No contaminant pathway testing was performed during this phase of the MUDS study. Therefore, the conceptual design of the upland did not specifically address potential design requirements for additional controls to reduce contaminant losses by specific pathways. It should be noted that while the testing cannot be done for the conceptual design, pathway testing is recommended for any site-specific design.

Contaminant control measures assumed for the upland conceptual design are focused on containment approaches in the form of a bottom liner and leachate collection system for one subcontainment and a surface cover for closure. The

effluent discharge water from the CDF is assumed to be treated to meet 401 permit requirements.

The conceptual design provides for multiple subcontainments or cells, with one cell lined and the remaining two cells unlined. For purposes of the conceptual design, the provision of the lined CDF cell is assumed to be sufficient to control contaminant losses by leaching for the materials with higher potential for such losses. Provisions for filtration are included to improve effluent quality by removal of contaminant laden suspended particles. Volatilization, surface runoff, and plant and animal uptake will be controlled after site closure by covering the contaminated dredged material with clean dredged material or soil.

It is assumed for the conceptual design that filter cells will be used for the upland CDF. These filtration devices would be constructed as an integral part of the dike. The cells are assumed to be constructed using sheet piles. A minimum of two filter cells would be placed at each outflow structure location. This would enable one cell to be operational while the other cell is being recharged in the event one cell becomes clogged. Each filter cell would have a diameter of approximately 9 m (30 ft). Coarse stone or gravel would be first placed in the bottom of the filter cell. Graded gravel would be placed on the top of the first layer. Sand will make up the majority of the filter cell. The filter cell structure will extend to the top of the dike. No additional effluent treatment beyond gravity settling and filtration is proposed.

The leachate collection system would be a layer of material (sand or graded gravel) that would be placed on top of the clay liner or geomembrane. The leachate collection system would have a head of 0.61 m (2 ft) above the liner. Perforated leachate collection pipe would be placed in this layer for the removal of leachate from the cell. The leachate would be transferred to a leachate treatment and disposal system. The leachate treatment and disposal system should be designed with a safety factor of 1.25 for effluent volume and contaminant load to be treated.

All material that will be placed in the upland CDF will be allowed to dewater and consolidate (see discussion in the following sections) before the final cover is placed on the site. There are no intermediate covers planned for the facility because of the recurring use of the site for contaminated material and the impact of multiple covers on capacity for contaminated material. The surface cover will be a clean material that has a hydraulic conductivity of 10^{-6} cm/sec and be at least 0.61 m (2 ft) thick. The topsoil layer should be a minimum of 305 mm (12 in.) thick and be able to support vegetative growth.

Dewatering Operations

For the conceptual design, dewatering will be limited to management of surface water following each filling operation and limited active measures to promote drainage of precipitation water in the intervals between filling. Periodic inspection and adjustment of the weir height will be necessary to drain surface

water and ensure that effective drainage continues as the newly placed material consolidates. Trenches will be constructed around the inside perimeter of confined disposal sites, especially near the weirs to promote increased drainage efficiency for rainwater. The material removed from the trenches will be placed against the inside face of the dike.

Conceptual Design for Upland Rehandling/ Dewatering Facility: Overview

The dredged material will be loaded onto barges and shipped to the barge offloading facility. The dredged material will then be mechanically offloaded into the dewatering facility or loaded onto trucks and hauled to the dewatering facility.

The rehandling option is sized for a throughput of approximately 19,000 to 23,000 cu m (25 to 30,000 cu yd) of dredged material. The site would occupy an area of approximately 12,100 sq m (3 acres) with a thickness of 1.83 m (6 ft) of sediment. The site would be divided into two cells with each cell containing 11,500 cu m (15,000 cu yd) of material. This is assuming that once the dredged material has been dewatered (within a 2-week time period), the dredged material would be removed and hauled to an appropriate disposal area. The overall dimensions and configuration for the dewatering facility design are shown in Figure 12.

Containment Dikes

The conceptual design for the dewatering facility dikes is the same as that for the upland CDF. The total volume requirement for the dewatering facility does not assume a volume reduction for the dredged material placed in each cell. The total volume of fill for the dewatering facility is approximately 19,000 to 23,000 cu m (25 to 30,000 cu yd) of material. Assuming an average depth of 1.83 m (6 ft) for the dredged material, the dikes would be approximately 2.4 m (8 ft) in height. This allows for 0.28 m (2 ft) of free board in the dewatering facility.

Like the first alternative for the upland CDF, the dike material for the dewatering facility is assumed to be constructed from onsite soils and could be characterized as clean fill. The material would be placed and compacted at optimum density. Side slopes of 3:1 are assumed for the construction of the main dikes. The top of the dike would be 6 m (20 ft) across to accommodate the movement of machinery around the site. For purposes of the conceptual design, these dimensions are assumed to meet required safety factors for stability under both static and seismic loadings for purposes of the conceptual design.

The overall length of the main dike for the dewatering facility is approximately 427 m (1,400 ft). This dike would be in a square shape as indicated in Figure 12. Site-specific design could dictate changes in the site geometry. One cross dike would be constructed to divide the dewatering facility into two cells.

Transport and Placement

The method for transporting dredged material to the dewatering facility is assumed to be by barge to off loading facilities. The dredged material will be placed in barges by clamshell and shipped to the barge offloading facility near the dewatering facility. The dredged material will be offloaded from the barge into the dewatering facility by mechanical means. This can be performed by using cranes to place the material into the dewatering facility, by using a conveyor system to place the material into the facility, or by placing the dredged material into trucks and hauling and placing the material into the dewatering facility.

Operation and Management

The operation and management of the dewatering facility is similar to that of the upland CDF. The surface area required for the total storage of the dredged material is assumed to be adequate for the primary settling of the material. The total volume of the site is assumed to be adequate for the initial storage during each placement of dredged material in the dewatering facility and for clarification efficiency (removal of suspended solids from excess water or surface runoff).

Figure 12 shows the location of the outflow structures for the conceptual design of the dewatering facility. Although only two outflow structures are shown in the figure, multiple structures can be used for the dewatering facility. The use of multiple outflow structures increases the control of the effluent from the dewatering facility so that acceptable water quality can be achieved. Weir heights should be adjustable for the full height of the anticipated fill plus ponding.

The surface water in the dewatering facility will be managed for 0.61 m (2 ft) of ponding during the placement of dredged material in the site. The water will be decanted from the dewatering facility immediately following any filling operation to encourage desiccation.

Contaminant Control Measures

No contaminant pathway testing was performed during this phase of the MUDS study. Therefore, the conceptual design of the dewatering facility did not specifically address potential design requirements for additional controls to reduce contaminant losses by specific pathways. It should be noted that while there can be no testing for the conceptual design, pathway testing is recommended for any site-specific design.

Suspended solids removal will primarily be by gravity settling as material is placed in the primary basins. If settling is not adequate to achieve 401 permit requirements, then flocculation and filtration can be used as needed to further remove suspended solids prior to discharge of effluent.

Filtration is typically used as a polishing step for water that has been pretreated by flocculation and/or sedimentation. Granular media filtration has been used to treat effluents at most in-water and some upland CDFs in the Great Lakes using filter dikes or filter cells. Permeable dikes provide gravity filtration through horizontal flow and are nonrenewable, once clogged. Most in-water CDF dikes constructed in the Great Lakes have a core of crushed stone. Some have discrete lenses of sand for filtration. Filter cells and sand-filled weirs are vertical-flow gravity filters that can be replaced or regenerated when exhausted. Filter cells may be incorporated into the CDF dike or can be freestanding structures.

It is assumed for the conceptual design that filter cells will be used for the dewatering facility . These filtration devices would be constructed as an integral part of the dike. The cells are assumed to be constructed using sheet piles. A minimum of two filter cells would be placed at each outflow structure location. This would enable one cell to be operational, while the other cell is being recharged in the event one cell becomes clogged. Each filter cell would have a diameter of approximately 9 m (30 ft). Coarse stone or gravel would be first placed in the bottom of the filter cell. Graded gravel would be placed on the top of the first layer. Sand will make up the majority of the filter cell. The filter cell structure will extend to the top of the dike. No additional effluent treatment beyond gravity settling and filtration is assumed necessary.

All material that will be placed in the dewatering facility will be allowed to dewater before the material is removed from the facility. There will be no intermediate covers for the dewatering facility.

Dewatering Operations

For the conceptual design, dewatering will be limited to management of surface water following each filling operation and limited active measures to promote drainage of precipitation water in the intervals between filling. Periodic

inspection and adjustment of the weir height will be necessary to drain surface water and ensure that effective drainage continues as the newly placed material consolidates. Trenches may be constructed around the inside perimeter of confined disposal sites, especially near the weirs to promote increased drainage efficiency for rainwater and minimize ponding of water in the facility. The material removed from the trenches will be placed against the inside face of the dike. Since the surface area of the individual subcontainments is relatively small, no interior trenching to further promote drying is deemed necessary.

Rehandling and Transport to Upland Disposal

The material from the rehandling facility will be removed on an annual basis and transported to an upland disposal site. For the conceptual design, rehandling by front-end loader or backhoe directly into trucks or placed in water tight standard 15-cu m (20-cu yd) or more refuse containers on rail flat cars for transport is assumed. The trucks will be lined, watertight, and equipped with covers to prevent spillage or loss of material during transport.

Design and Performance Standards for Upland CDFs and Upland Rehandling/ Dewatering Facilities

This section provides narrative and, where appropriate, numerical design and performance standards for the MUDS upland CDF and rehandling/ dewatering options. The proposed standards are intended to be applied to a site-specific design should an upland option be selected for MUDS. The standards are based on available technical guidance in the literature, as well as available design information from projects nationwide and within Puget Sound. Although the design of a MUDS alternative would not strictly be considered as a functional design, the proposed standards in this section are technically compatible with design standards. The standards for various aspects of the design are stated in the following paragraphs, and all the proposed standards are summarized in Table 4.

Overall design and performance objectives for upland options

An overall design objective for an upland CDF is to provide sufficient diked volumetric capacity to accommodate the required volume of dredged material and contain the dredged material such that any releases of contaminants from the site will be within acceptable limits. The overall objective for a rehandling facility is similar, except the facility will provide sufficient capacity for an annual throughput.

Table 4
Design and Performance Criteria for Upland CDFs and Upland Rehandling/Dewatering Facilities

Item or Category	Performance Criterion
Overall design objective	Sufficient capacity provided; contain the dredged material such that any releases of contaminants from the site will be within acceptable limits.
Engineering design	Design completed by competent professional engineers; standard USACE engineering design documents will be applied as appropriate.
Environmental evaluations	Sites evaluated in accordance with the USACE/EPA Technical Framework (1992).
Dike height	Height determined by considering capacity requirements, anticipated end use of the site, once filled.
Dike stability	Dike of the embankment type must meet a safety factor of 1.0 to 1.5 against slope failure, depending on the loading condition; design must meet a safety factor of 1.5 against liquefaction of the embankment and/or foundation.
Dredging and Placement/offloading	Solids retention to be accommodated and spillage and leakage minimized; contaminated sediments dredged by mechanical clamshell and transported from the dredging site to the rehandling site by haul barge; no overflow; flat deck barges with side boards will be watertight; shallow hull barges, if split-hull or bottom-hopper door type, shall have a hydraulic checking procedure; sediments off-loaded at the approved site by clamshell, backhoe, or front-end loader; no stockpiling of materials for rehandling will be allowed; rehandling area will be contained to allow catchment and control of incidental contaminated sediments misplaced during the offloading operation.
Outlet (weir) structures	Sized to pass 25-year rainfall event plus flow rate for offloading.
Site operations/ sequencing	As scheduling will allow, initially place materials with lower potential for adverse impact; materials with higher levels of contamination sandwiched between layers of lower contamination.
Solids retention	Site operated to ensure that applicable water quality standards for total suspended solids (TSS) or turbidity are met at the boundary of the designated mixing zone; adequate ponded surface area and water depth will be maintained during hydraulic filling operations.
Effluent quality	Dissolved contaminant concentrations will not exceed applicable acute water quality standards, and effluent will not exceed applicable water column toxicity criteria at the boundary of the designated mixing zone.
Surface runoff	Site operated to contain runoff from 25-year storm event for controlled release with quality same as for effluent.
Leachate quality	Dissolved leachate contaminant concentrations will not exceed applicable groundwater quality standards at the boundary of the designated attenuation or mixing zone.
Direct uptake	Site operated and managed such that measured tissue concentrations in plants and animals do not exceed applicable FDA action levels and applicable ecological risk criteria/guidelines.
Volatilization	Site operated and managed such that measured air concentrations do not exceed applicable air quality standards.
Dewatering	Volumetric disposal capacity maximized to the greatest extent feasible.
Final cover	Designed to control surface runoff and direct uptake by plants and animals; final cover placed following initial consolidation and dewatering; final cover an engineered design appropriate for future site use, e.g. site vegetation, armoring with larger grain-size sediments, or paving.
Transport from Rehandling Facility	Final haul overland to the disposal site will be required; method of contaminated sediment haul to an upland disposal site will be by approved carrier only; transport from the dewatering site to the disposal site will use only lined, watertight, and covered haul equipment; no contaminated sediments will be dropped or misplaced during transit; any materials accidentally misplaced will be recovered immediately and disposed at the approved disposal site.

Engineering design procedures

The site design will be completed by competent professional engineers and standard USACE engineering design documents will be applied as appropriate in the design (a listing of USACE Engineer Manuals and other design documents is given in the "Index of Publications," EP-25-1-1 (HQDOA 1995b)).

Environmental evaluations and contaminant pathway controls

Environmental evaluations conducted as a part of the design will be in accordance with the Technical Framework (USACE/EPA 1992).

Dike height

The constructed dike height for an upland CDF will be determined considering capacity requirements, surface area requirements, ponding requirements for any hydraulic filling, and the anticipated end use of the site, once filled.

Retaining dike stability

Upland retaining dikes require all pertinent aspects of formal geotechnical design. Depending on the design alternatives, sliding, overturning, as well as slope instability must be thoroughly investigated. Soft foundation conditions can lead to shear failures in the foundation as well as erosion at the toe of the structure. Other loadings of concern may be earthquake loads, or even the active and passive soil pressures in the confined material itself pushing outward on the dike, especially if the structure is filled to near crest elevations.

The stability of the structure must be addressed from both static and dynamic points of view. Guidance for design practice and required factors of safety which are probably most pertinent to upland retention structures is found in the following USACE Engineer Manuals:

EM 1110-2-1902, "Stability of Earth and Rock-Fill Dams" (Revision of this EM is nearing completion under the new and more general title, "Shear Strength and Slope Stability") (HQDOA in preparation)

EM 1110-1-1904, "Settlement Analysis" (HQDOA 1990)

Engineering Regulation ER 1110-2-1806, "Earthquake Design and Evaluation for Civil Works Projects" (HQDOA 1995a)

Static stability

EM 1110-2-1902 (HQDOA 1970a) provides minimum factors of safety for all cases where the structure is an earthen embankment and other types of structures where stability checks must be made against failure through the foundation soils. In accordance with these criteria, the design of a dike of the embankment type will meet a safety factor of 1.0 to 1.5 against slope failure, depending on the loading condition.

Dynamic stability

Earthquake design criteria are not yet formalized in an Engineer Manual. Current practice cites a minimum factor of safety of 1.50 against liquefaction of the embankment and/or foundation. In any event, earthquake considerations are a specialty concern within geotechnical engineering and require the input of the appropriate regional experts with respect to the establishment of the design earthquake to the analyses of its effects. Therefore, safe design is not a conventional procedure and must be addressed by the qualified specialists.

A sequence of steps should be followed in evaluating ground motions and performing seismic analyses for earth, concrete, and steel structures (after Krinitzsky, Hynes, and Franklin 1996, revised by Krinitzsky 1997). These steps, as applied to containment dikes, are as follows:

a. *Determine level of criticality.* What is the required safety margin? What is the allowable level of damage? Are the consequences of failure intolerable - fatalities, economic and environmental losses?

b. *Determine earthquake category.* If the structure is critical (intolerable consequences of failure defined as breaching of dike and significant flow or release of contained sediments), then the design basis earthquake (DBE) should be the maximum credible earthquake (MCE) determined from a site-specific evaluation of seismic sources, maximum possible magnitudes, and attenuation over the closest distance to the site of mean-plus-one-sigma motions. If the structure is less than critical, then the DBE should be selected as a risk-consequence balanced earthquake (RCE) based on all the information determined for the MCE plus a probabilistic seismic hazard analysis incorporating the frequency of earthquake occurrence and an assessment of consequences of failure.

c. *Evaluate seismic hazard.* Identify seismic sources that could affect the site; establish maximum credible events for each source and historical seismic activity; establish DBE as MCE or perform risk analysis to determine RCE; attenuate DBE motion from each controlling source to the site to determine peak ground motions parameters and response spectra for analysis.

d. Determine foundation conditions and liquefaction susceptibility. In addition to the usual foundation investigation for static loads, determine shear wave velocity profiles, perform Cone Penetration Tests (CPT) and/or Standard Penetration Tests (SPT) according to liquefaction evaluation requirements. Collect samples to determine gradations, fines contents (percent passing the number 200 sieve), plasticity of fines, water content, and in situ density. For cohesionless materials, determine relative density of foundation soils. Evaluate liquefaction susceptibility using DBE motions, and determine areal extent, thickness, and depth of liquefiable materials. Evaluate liquefaction potential and stability of shore abutment for fill and dikes.

e. Design dike for combined static and seismic loads. Design dike materials to be nonliquefiable for the DBE (for example, use compacted rolled-fill for upland dikes, and clean rock fill with a flexible core and filter system, possibly with geosynthetics, for nearshore dikes). If liquefiable materials are present in the foundation, assign residual strengths to them and evaluate design alternatives. If liquefiable materials are present over a large area, they may need to be removed or improved. Experience in California indicates that hydraulically placed materials generally do not liquefy at peak acceleration levels less than 0.15 g for earthquakes with magnitudes of 6 or less (A difficulty with probabilistically determined DBE motions is that magnitude levels are obscured). If the DBE motions are less than this threshold event, then the dredged fill might not liquefy and some level of shear strength could be assumed for the contained fill. If the DBE motions are equal to or more severe than this event, assume that the contained fill has no shear strength and imposes a heavy fluid load on the dike and may include hydrodynamic effects. Analyze pseudo-static slope stability and translation (determine yield accelerations for these failure modes), potential Newmark-sliding block movement, bearing capacity, and settlement of the dike. Several feet of outward movement and/or settlement of the dike may be acceptable if defensive measures are incorporated in the dike design and repairs, if needed, can be constructed in a timely manner after the earthquake.

Dredging and placement methods/offloading facilities for contaminated sediments

For barge offloading, a special offloading facility will be needed. This facility must be large enough to accommodate an offloading crane and several trucks or containers with a capacity of more than 15 cu m (20 cu yd). The material will be offloaded from the barge directly into trucks or containers and hauled to the CDF or rehandling facility. For hydraulic offloading, a different facility will be needed that uses a pump to offload barges. Such a facility has been used at the Hart Miller Nearshore or upland site near Baltimore. A hydraulic offloader with a 610-mm (24-in.) main pump capable of discharging 2,000 cu m (2,500 cu yd) per hour through lines of up to 5,486 m (18,000 ft) was also used for the Sonoma Baylands project in San Francisco Bay (World

Dredging Mining and Construction 1996). Such offloading facilities consist of an offloader which is essentially a specially configured hydraulic pipeline dredge. The offloader head is equipped with water jets to introduce slurry water into the barge to allow for pumping of the relatively low water content material resulting from mechanical dredging. Offloading pumpout facilities can be sized to offload barges, with flow rate matched with available ponded surface area to accommodate solids retention requirements.

Spillage and leakage are concerns for hydraulic offloading facilities involving pipelines. Special controls such as hydraulic checks should be considered to prevent significant spills in the event of a pipeline break. Offloading facilities will have appropriate provisions to minimize spillage and leakage.

Weir structures

Weir structures will be required to allow discharge of the excess carrier water as effluent during active filling. The flow rate of effluent discharge will be determined by the rate of filling. Weir structures will be sized to pass a design discharge consisting of rainfall runoff for a 25-year rainfall event plus flow rate for the largest offloading pump. If multiple weir locations are selected for purposes of site management, each of the structures should be sized to pass the design effluent discharge flow rate. The CDF should also be designed to accommodate an emergency draw down of ponded water if required.

Fill height/sequencing

Although a detailed site operations plan will be required and must be based on the specific configuration and conditions for the selected site, some preliminary site operation principals with respect to fill height and sequencing can be considered. The final fill height must account for a final cover of clean material (see discussion below regarding final closure).

If scheduling of dredging projects will allow, materials with lower potential for adverse impact should be placed in the CDF in the initial stages of filling. This would provide a layer of clean materials against the base of the dike and bottom of the CDF to act as an ad hoc liner to retard and attenuate leachate from later placement of more contaminated materials. The use of cleaner material for the final layers will be used to provide insurance for the capping material.

Sequencing is not a major consideration for a rehandling facility since materials would be removed from the facility on a recurring basis for final disposal.

Suspended solids retention

A CDF must be designed and operated to provide adequate initial storage volume and surface area to retain suspended solids such that clarified water is released or discharged. The area of ponded water within the facility will be minimized.

Contaminant Release Pathways

A CDF for contaminated sediments must be designed to contain dredged material within the site and restrict contaminant mobility out of the site in order to control or minimize potential environmental impacts. Several possible mechanisms or pathways for transport of contaminants from a CDF should be considered:

a. Release of contaminants in the effluent during disposal operations.

b. Surface runoff of contaminants as a result of precipitation.

c. Leaching into groundwater.

d. Uptake by plants or animals directly from sediments, or by indirect animal uptake from feeding on vegetation.

e. Gaseous or volatile emissions during and after placement of dredged material.

Each of these potential pathways will require consideration of specific design or performance standards. For a rehandling facility, the contaminant pathways must also be considered, but the filling and emptying schedule will also influence the nature of the control measures required.

Effluent quality

Effluent is the discharge or release of water during active filling operations. Effluent is considered a dredged material discharge under Section 404 of the CWA. State water quality certification will determine standards that must be met. The site will be designed and operated such that dissolved effluent contaminant concentrations will not exceed applicable acute water quality standards at the boundary of the designated mixing zone. Further, the effluent will not exceed applicable water column toxicity criteria at the boundary of the designated mixing zone.

Surface runoff

Water may be decanted from the surface of the settled material between active filling operations. Material is then exposed to runoff after precipitation.

Runoff may be governed by the 401 water quality certification, or considered as a part of the NEPA process. It may be desirable to pond runoff water to allow the eroded suspended material to settle prior to discharge of the runoff water. The site and weir structures will be designed and operated to contain runoff from a 25-year storm event for controlled release. The site will be designed and operated such that dissolved runoff contaminant concentrations will not exceed applicable acute water quality standards at the boundary of the designated mixing zone. Further, the concentrations of suspended dredged material discharged as runoff will not exceed applicable water column toxicity criteria at the boundary of the designated mixing zone.

Groundwater leachate and dike seepage

Leachate refers to water that passes through dredged material in a CDF and flows into groundwater beneath the site or through the dikes. As the fill rises, the hydraulic gradient for such leachate flow will increase. For upland site, the protection of a groundwater resource is a major concern. From a regulatory standpoint, leachate may fall under the 401 water quality certification or considered as a part of the NEPA process. The site will be designed and operated such that dissolved leachate contaminant concentrations will not exceed applicable state groundwater water quality standards at the boundary of the designated zone of attenuation (mixing zone) and will meet the requirements of the State Solid Waste Management Act. A lined cell and leachate collection system will be used in the event that contaminated material is placed in the facility.

Direct uptake

The exposed surface may become colonized with plants and animals. Some contaminants can be bioaccumulated in plant tissue and become further available to the food chain. The site can be operated and managed to discourage certain species from colonization. Measured uptake concentrations in bioassays or in organisms collected on the site can be compared to various criteria, to include Food and Drug Administration (FDA) action levels for plants and foodstuffs (Lee et al. 1991). Appropriate criteria for direct uptake may be considered as a part of the NEPA process. The site will be operated and managed such that measured tissue concentrations in plants and animals colonizing the site do not exceed applicable FDA action levels and ecological risk criteria guidelines. Site management must also include measures to reduce potential risks to all environmental receptors.

Volatilization

Volatilization of contaminants directly from exposed sediment to air is only a potential concern for sediments with relatively high levels of volatile organics. Air-quality criteria may be considered as a part of the NEPA process. The site

will be operated and managed such that measured air concentrations do not exceed applicable air-quality standards.

Management for Dewatering and Long-Term Storage

The design and operation of the CDF should allow for efficient use and increases in the volumetric capacity available for disposal. Increase in storage capacity results from decreases in the height of dredged fill deposited over the long-term due to consolidation and drying or desiccation. The site will be operated and managed to maximize volumetric disposal capacity and dewater and density fine-grained material to the greatest extent feasible. Site operation and management for dewatering includes decanting the ponded water from the site whenever possible to expose the surface to drying. The most economical dewatering approach is to construct trenches around the site periphery and within the interior of the site to promote efficient surface drainage of precipitation and increase the effective rate of drying.

Final cover

Once the dredged material fill has reached its limiting height in the CDF, appropriate management and other control measures should be considered to allow for long-term site use. Physical isolation of the material to prevent direct human contact and uptake by organisms colonizing the site by placement of a surface cover would be the most efficient means. A layer of suitable material will be placed to act as a final surface cover. The cover design, to include thickness and composition of the layer, will provide an effective control for the surface runoff, and direct uptake pathways for plants or animals.

Since an upland MUDS site will likely be developed, once the air is filled, the intended end use of the site may dictate other structural requirements for the cover design. The cover for an upland site will be placed following initial consolidation and dewatering and will require an engineered design appropriate for future site use, e.g., site vegetation, armoring with larger grain size sediments, or paving (Parametrix, Inc. 1990).

Transportation of rehandled material

Final haul overland to the disposal site will be required. The method of contaminated sediment haul to an upland disposal site will be by approved carrier only. Transport from the dewatering site to the disposal site will use only lined, watertight, and covered haul equipment. No contaminated sediments will be dropped or misplaced during transit. Any materials accidentally misplaced will be recovered immediately and disposed at the approved disposal site (Parametrix, Inc. 1990).

3 Nearshore Confined Disposal Facilities

Description, Definitions, and Application

Nearshore confined disposal is placement of dredged material within confined (diked) disposal facilities (CDFs) via barge, conveyor, bucket, pipeline, or other means at a site constructed partially or completely in water adjacent to the shore. A true nearshore site will take advantage of the shoreline as a part of the containment structure for the site, with in-water dikes or other containment structures required only for the remaining walls of the total enclosure. Nearshore CDFs discussed in this section have dikes with crest elevations above the mean high high water (MHHW). However, highly contaminated dredged material is usually placed below the mean tide level (MTL) elevation, and cleaner dredged material or other capping material is placed above the MTL mark.

Nearshore CDF applications

Nearshore CDFs are most numerous in the Great Lakes region of the United States. Many of these sites were constructed adjacent to entrance channels or harbor channels. Large nearshore sites--CDFs initially constructed in water and which are now upland sites--are located in Puget Sound, the Great Lakes area, the Atlantic Coast, and California.

In Puget Sound, a number of nearshore sites have taken advantage of existing piers or other terminal facilities to provide two or three of the dikes for the CDF. The Terminal 91 Short Fill Project for the Port of Seattle consisted of placing two berms spaced about 120 m (396 ft) apart across the slip between the solid-fill piers of Piers 90 and 91. Approximately 100,000 cu m of contaminated dredged material was placed in the site using a bottom dump barge that moved into the CDF through a notch in the dike (Boatman and Hotchkiss 1997, Converse Consultants 1992). The Port of Tacoma constructed a containment berm across the Milwaukee Waterway to contain remediation dredged material from the Sitcum Waterway and navigation dredged material from the Blair

Waterway (Verduin, Saathoff, and Horvitz 1994). Dredged material from the Sitcum project was dredged mechanically and barged into the site prior to raising the berm to final elevation. In the final stages of the project material was added to the site using a hydraulic pipeline dredge. The Port of Everett also used a nearshore CDF for its Marine Terminal Improvement Project (Hartman Associates 1996). Several Puget Sound sites have been capped with clean material and converted to container facilities or parking areas.

The Southwest Harbor Cleanup and Redevelopment Project proposed a submerged nearshore CDF option with the potential to serve multiple users. This CDF would have represented a combination nearshore diked facility and contained aquatic disposal facility. The crests of the berms were to be below MHHW (Parametrix, Inc. 1994a,b, Washington State Department of Ecology 1994). Design considerations and migration pathways for such facilities are closely related to those for the contained aquatic alternative. Though the Southwest Harbor project was not implemented, it will be considered as an alternative for placement of dredged materials for the proposed East Waterway maintenance dredging project. The Corps of Engineers and the Port of Seattle will prepare a joint Environmental Impact Statement (EIS) for this project.

Island CDFs

Island CDFs are similar to nearshore CDFs, except that they are constructed totally in water with no direct physical connection to the shore. Due primarily to water depths in Puget Sound, island CDFs would only be feasible constructed near the shoreline and are not considered as a separate alternative.

Contaminant Pathways

Migration pathways potentially affected by nearshore CDFs are illustrated in Figure 13. Pathways for nearshore CDFs differ from those for upland CDFs as a result of placement of contaminated material below MTL. The relative importance of the nearshore pathways is influenced by site conditions, groundwater flows, tidal fluctuations, and sediment characteristics. The more significant pathways for a MUDS CDF are shown in Figure 14. A primary advantage of the nearshore CDF is that the contaminated dredged material remains within the saturated zone so that anaerobic conditions prevail and contaminant mobility is minimized. Tidal action through the exterior berms, which are generally constructed of permeable material is one of the primary contaminant loss pathways for a nearshore CDF. Tidal dispersion will increase the flux, but lower the concentration, as a result of dispersive mixing. Groundwater gradients through the contaminated sediment in a nearshore CDF are reduced because of fresh water, being less dense than salt water, moving above the salt water wedge and minimizing contact with the contaminated dredged material (Riley et al. 1994). Groundwater flow is also directed upward by the reduced hydraulic conductivity of the contaminated sediments compared

to berm and capping materials. The movement of fresh groundwater through the dredged material will eventually (many decades for most sites) wash out the salinity. Laboratory column studies have shown that leaching of estuarine sediments with low-ionic strength water results in destabilization of the colloidal system as salt is washed out. As colloids are released, so are colloid-bound contaminants (Myers, Brannon, Tardy, and Townsend 1996). That portion of a nearshore CDF raised to above the mean high-water elevation will essentially function as an upland CDF. Additional considerations for nearshore sites (with one or more sides within the influence of water level fluctuations) are soluble diffusion from the saturated zone through the dike and leachate flow through the bottom of the site and the dikes. These flows are driven by pore pressures during consolidation of the dredged material and the potential increased hydraulic head inside the dikes compared to outside the dikes. The discharge of effluent or surface runoff through the weir for a mechanically filled CDF is a relatively minor pathway during active filling of the CDF. Volatilization is also reduced by the ponded water covering the contaminated dredged material during active filling and by the cap after closure. Biological uptake may be a concern for avian inhabitants of the CDF.

Several studies in Puget Sound have reported that berms function as treatment cells through the occurrence of major biogeochemical processes. Boatman and Hotchkiss (1997) modeled flow and contaminant transport through the Terminal 91 and Southwest Harbor nearshore fills to show that organic contaminants were biodegraded via aerobic and anaerobic oxidation, and mobility of metals and organic contaminants was reduced through coprecipitation and adsorption occurring within the berms.

Previous investigations of Puget Sound nearshore CDFs have suggested that liners, impermeable dikes, and other leachate controls are not necessary for environmental protection. Effluent control measures are not likely required for these nearshore CDFs, because they are usually filled by mechanically dredged material, rather than hydraulically pumped material. Water levels will remain above the contaminated material during most of the useful life of the site, minimizing the volatilization pathway and eliminating concern for storm water runoff. Once the dredged material elevation rises above the MHHW level, the site will be capped with clean material to minimize the effects of these pathways. Procedures for evaluating contaminant migration pathways are provided by USACE/EPA (1992), Francingues et al. (1985), and USEPA/GLNPO (1994a,b,c). However, consideration of some controls such as liners for the leachate pathway present special design and construction problems for in-water CDFs.

Processes and Design Considerations

There are several issues which must be carefully considered within the context of a nearshore CDF design:

a. *Retaining dikes.* The site conditions must allow for construction of structurally and geotechnically sound retaining dikes for long-term containment of dredged material solids and contaminants. The dike face will also be exposed to erosional forces due to currents and wave action, and some form of armor protection would normally be considered. Since the dikes must be constructed in water, marine construction techniques must be used, and these normally result in increased costs as compared to upland sites.

b. *Transport and placement of material.* Nearshore sites have waterfront access by definition. Material can be transported from dredging areas to a nearshore site by barge and directly offloaded to the site by mechanical rehandling or by hydraulic reslurry operations. Another technique used for Pier 91, the Port of Everett, and the Milwaukee Waterway site for material placed below MHHW is to leave a notch in the berm at el 1.5 to 3 m (5 to 10 ft) below MLLW. Dredged material is moved into the site contained in the barge and the barge hopper opened allowing the material to drop into the CDF. Once the elevation of the dredged material precludes movement of the barge into the facility, the dredged material must be unloaded by crane over the dike to a conveyor belt, or slurried in the barge and pumped into the facility. As the dredged material and cap rise above MHHW, low ground pressure earthmoving equipment may be used to spread the additional capping material by conventional earthmoving techniques. Placement by direct pipeline from hydraulic dredges is feasible if the site is located near dredging areas.

c. *Site geometry and sizing* . The site must be volumetrically large enough to meet both short-term storage capacity requirements during filling operations and long-term requirements for the anticipated life of the site. Sufficient surface area and dike height with freeboard must be available for retention of fine-grained material that may be resuspended during filling or storm events.

d.. *Contaminant pathway controls.* Provisions for control of contaminant release through any of several pathways must be considered in the site design. These may include cutoff walls for groundwater moving from upgradient toward the site and provisions to minimize biological uptake of contaminants if a notch in the berm is open.

e. *Dewatering and long-term management.* A nearshore site can be managed for dewatering of material above MHHW. Dewatering of material in the saturated zone is limited by consolidation processes. If material is mechanically offloaded from the barge to the CDF, additional water is reduced compared to hydraulic offloading.

Each of these considerations must be appropriately addressed by the project design. More detailed discussion of these processes and design considerations is given in the following paragraphs.

Containment Dikes

Containment dikes for nearshore sites must consider site-specific geotechnical conditions, wave effects, maintenance requirements, and seismic effects. Most Puget Sound in-water dikes have used sand and gravel as fill material. Soft foundation material along the center line of the berm may require excavation prior to placement of the fill to provide a suitable base for the berm. Rock fill dikes are more commonly found in the Great Lakes. Structures such as sheet-pile walls or cellular cofferdams have also been used for nearshore CDFs.

For CDFs situated in the water, the retaining dikes require protection from erosion due to waves. The erosion protection is generally an armor layer(s) made of rock, the size and extent (and cost) are a function of the severity of the wave climate. Depending on the size of the waves, the armor layer can have more than one layer of rock, progressing from small rock or gravel on an inner layer to the largest rock on the outer layer.

Engineering design of the CDF armor layer requires at a minimum defining the water depth where the CDF will be located, determining the wave climate and selecting a design wave, determining water levels, and deciding if wave run-up and overtopping need to be considered. From this information, the stable rock size, number of rock layers, and extent of the armor layer both above and below the waterline can be determined. The depth of water in which the CDF is located can also have a major impact on the CDF erosion protection design. As water depths increase, costs often increase due to the increased potential for larger waves.

In designing the armor layer for an in-water CDF, the most important information required is the wave climate. Based on the wave climate, a design wave is generally selected. The design wave is often the most severe wave expected in a return period ranging from 50 to 100 years. A risk-based approach balancing expected damages against initial costs is often used to determine the optimum design. Other factors relating to water levels and waves also need to be considered in design of the CDF erosion protection. Knowledge of the potential changes in water level, primarily resulting from tides and wind setup, is required. If the CDF is adjacent to shipping lanes, waves generated from a passing vessel may be a concern. The combination of waves and water levels determines runup which influences how high up the dike the erosion protection should extend. Depending on the height of the dike, waves can reach over the top of the dike.

CDF armor layer design should be conducted by an experienced coastal engineer, assisted by geotechnical engineers. The design of the armor layer should be integrated with the CDF dike design.

Transport and Placement

The method selected for transfer of dredged material from dredging areas to a nearshore CDF is dependent on the dredging technology used in the excavation of the sediments. Nearshore CDFs may be filled by mechanically rehandling dredged material from barges as described earlier. Material placed in the CDF in this manner is near its in situ water content. If such sites are constructed in water, the effluent volume may be limited to the water displaced by the dredged material, and the settling behavior of the material is not an important factor. Direct placement of material by pipeline dredge is economical if the site is located near the dredging areas.

If barges are used for transport, the sediment may be transferred from the barge to the CDF by several methods depending on the distance of the CDF from point of closest access by the barge. Unloading methods include the following:

a. Clamshell the dredged material from the barge directly into the CDF using a chute or other conveyance to transfer the dredged material beyond the interior toe of the dike.

b. Transfer material from the barge directly into the CDF by using a dragline bucket.

c. Unload the material from a flat-deck barge using a front-end loader and transport over the berm and into the CDF.

d. Clamshell to a conveyor belt transferring the dredged material over the dike to the CDF

e. Provide a notch in the berm to allow a barge loaded with sediment to be moved into the CDF interior where the barge is emptied through a split-hull or bottom-dump barge. Opened or enclosed flat-deck barges may also be used where barge draft is critical due to shallow water. Material from the flat deck is unloaded with a front-end loader or bucket. (Hartman Associates 1996)

f. Slurry the material in the barge by adding water and mixing and pump the slurry through a pipeline to the CDF.

Initial Storage Capacity and Solids Retention

Design for initial storage capacity for material mechanically (not hydraulically) dredged and offloaded into the CDF is generally not critical. The dredged material will gain additional water and volume, estimated at less than 20 percent, during the dredging process. Once the material is placed in the CDF, it will consolidate over the course of the life of the facility to its original volume or less due to the added thickness of the fill compared to its in situ locale.

Therefore, designing the CDF volume for the original (mechanically dredged and filled) sediment volume is conservative. However, if the CDF is filled hydraulically, the dredged material will initially increase to several times its original volume, depending on sediment characteristics and dredging technique. This volume increase becomes potentially important for design of a long-term storage site only as the CDF approaches design capacity and storage depth, hence volume, is limited.

Nearshore CDFs will be filled with water from the Sound during the initial stages of filling. The volume of water potentially discharged as effluent will be equal to or less than the volume of materials placed in the site. This water may be released through a permeable dike during ebb tides. For mechanically placed material, suspended solids will increase inside the CDF during filling. Solids suspended in salt water often flocculate and settle in a matter of hours. Those solids that do not settle will be filtered as excess water is released through the dikes. Surface area for solids retention during mechanical filling is not a critical criterion for a nearshore MUDS site. Once the fill breaks the water surface, effluent will be formed by surface runoff. However, since the surface sediment is clean, the storm water should be relatively clean. If the CDF were filled hydraulically, surface area for solids retention would be more important, but not likely a controlling factor for a long-term site. Considerations for retention of suspended solids during hydraulic filling operations above MHHW are similar to that for an upland site (HQDOA 1987). A notched-dike option would increase the potential for release of suspended solids during mechanical or hydraulic filling. This release could be reduced by managing the offloading or barge dumping operations and/or by using turbidity barriers.

Pathway Testing and Evaluation

Nearshore geochemical environment

CDFs constructed totally or partially in water will usually receive dredged material until the final elevation is above the high-water elevation. Three distinct physicochemical environments may eventually exist at such a site: upland (dry unsaturated layer), intermediate (partially or intermittently saturated layer), and aquatic (totally saturated layer) (Lee et al. 1986).

When material is initially placed in an in-water CDF, it will all be flooded or saturated throughout the vertical profile. The saturated condition is anaerobic and reduced, which favors immobility of organic and heavy metal contaminants. Maintaining conditions in the saturated zone of the CDF similar to those at the site of dredging takes advantage of the relatively stable geochemical conditions for fine-grain sediments and contaminants. Most contaminants remain tightly sorbed to the sediment fines and organic matter.

After the site is filled and dredging ceases, the dredged material above the high-water level begins to dewater and consolidate through movement of water

upward and out of the site as surface drainage or runoff and laterally as seepage through the dike. At this point, the surface layer has characteristics similar to that of material in an upland CDF. As the material desiccates through evapotranspiration, it becomes aerobic and oxidized, conditions favorable for mobilization of heavy metals. Therefore, material placed above the MHHW level should be relatively clean material.

The bottom of an in-water CDF below the low tide or groundwater elevation remains saturated and anaerobic, favoring insolubility and contaminant attraction to particulate matter. After dewatering of the dredged material above the flooded zone ceases and consolidation of the material in the flooded zone reaches its final state, water movement through the flooded material is minimal and the potential for migration of contaminants is low.

The intermediate layer between the saturated and unsaturated layers will be a transition zone and may alternately be saturated and unsaturated as the water surface fluctuates. The depth of this zone and the volume of dredged material affected depend on the difference in tide elevations and on the permeability of the dike and of the dredged material.

Analysis of Pathways for Nearshore CDFs

Analysis of CDF pathways for nearshore sites includes several of the same tests used for upland sites. Procedures used to estimate the additional potential fluxes for the in-water CDF have been used in a number of in-water CDF evaluations (USAEWES 1987; Francingues and Averett 1988; Palermo et al. 1989). A number of these protocols have been used in Puget Sound projects, such as Southwest Harbor, Everett, and Milwaukee Waterway. One key difference is the analysis of the leachate pathway. Procedures tailored to the anaerobic environment are applicable to the dredged material layer that remains saturated in the nearshore environment. Ponded conditions that normally exist in nearshore or in-water CDFs can limit concerns with the volatilization pathway. The surface runoff would only be of concern if the dredged material fill is raised above the mean high-water elevation. Ideally, clean material would be placed above MHHW. One pathway of concern is the plant and animal pathway. Benthic in fauna will likely colonize in the material placed inside the CDF. If a notched dike for barge movement in and out of the site is used, fish and other aquatic life may pass in and out of the site picking up contaminants in their food chain. To reduce this potential, a moveable barrier, such as a silt curtain or wire mesh, could be placed across the notch except when a barge is entering and exiting the CDF. However, the effectiveness of a temporary barrier is limited. A more elaborate system similar to a navigation lock would be more effective but would add significantly to the cost of the site. The USACE/EPA Technical Framework and the Comprehensive Analysis of Migration Pathways (CAMP) (USACE/EPA 1992; Myers 1990; USEPA/GLNPO 1994a,b,c) describe appropriate testing and evaluation procedures.

Contaminant Control Measures for Nearshore CDFs

Considerations for selection of management actions and contaminant controls for nearshore CDFs are described in (USACE 1987; Francingues et al. 1985; Cullinane et al. 1986; Averett et al. 1990; USEPA/GLNPO 1996a,b,c). However, the geochemical conditions for nearshore fills reduce the need for leachate and effluent controls. An impermeable barrier to groundwater flow to divert groundwater flow from the shoreline into the CDF may be beneficial for some sites but is not a standard design feature for Puget Sound CDFs. Controls such as liners, leachate collection or groundwater pumping, and subsurface drainage would not be feasible for in-water sites.

Monitoring Nearshore CDFs

Monitoring a nearshore CDF is similar to monitoring for an upland CDF. However, the effluent discharge rate will be influenced by the water elevation on the outside of the dike. Analysis of groundwater effects by contaminant leaching is more difficult than an upland site because of more external impacts on groundwater elevations and flows. While groundwater effects for upland sites may include impacts to drinking water supplies, groundwater is important for nearshore CDFs primarily as a contaminant transport mechanism to adjacent surface waters.

Monitoring was conducted at the Terminal 91 nearshore CDF site in Elliott Bay for 5 years (Hotchkiss 1988; Converse Consultants 1992). The goals of the monitoring program were to monitor and demonstrate facility performance and to gain a better understanding of the physical and biogeochemical processes occurring within the berm. The monitoring data showed that the majority of tidal dispersion and mixing within the berm occurs in the intertidal and shallow subtidal zone, with major flow from the facility occurring on the lower-low ebb tide. The data also showed that both dilution and treatment occurred within tidally active portion of the berm (Boatman and Hotchkiss 1997).

Boatman and Devol (1995) reported methods for measuring the contaminant flux from in situ sediments. A high-resolution (millimeter interval) interfacial pore water sampler and a benthic flux chamber sampling device produced data for comparison to a numerical fluid flow and transport model for a nearshore CDF.

There was also a relevant predesign study for a proposed nearshore CDF at Southwest Harbor in Elliott Bay, which used a numerical model to predict the pathways, fluxes, and concentrations from the proposed nearshore CDF. The model included tides and density-dependent flow to simulate the effects of the difference in fluid density between fresh and salt water on the flow and transport (Hotchkiss and Boatman 1994; Boatman and Hotchkiss 1997). The modeling

results showed that: the net flow through the fill is strongly influenced by the density difference along the freshwater/saltwater interface; fresh upland groundwater flow is directed upward as it approaches the more dense salt water, which enhances the net outward flow in the lower intertidal and shallow subtidal zone; greater than 95 percent of flux of contaminants occur in this zone and the flux is increased from 10 to 100 fold from tidal dispersion, while concentrations are lower; however, the contaminant fluxes and concentrations were much more sensitive to the processes occurring within the berm than to the hydraulic flow parameters.

These studies show that monitoring can be accomplished using wells within the berm that are screened in the lower intertidal and shallow subtidal zone. In this instance, sampling should occur only during the lower low tide, and a reasonable dilution ratio must be applied to the results to account for dilution from the wells to the berm face. There are presently several nearshore CDFs in Puget Sound that have been or are being monitored using similar protocols (Terminal 91 and Eagle Harbor) and one site (Everett) in which wells will be installed. Site-specific factors can modify this, however. The Milwaukee Waterway (Tacoma, WA) fill, for example, contains physical considerations which do not warrant this type of sampling.

To understand the fate of contaminants in nearshore CDFs and to design sites that take advantage of natural processes for controlling and/or degrading contaminants, monitoring programs should include detailed geohydrology over the tidal cycle, existing groundwater chemistry, and pore water chemistry for dredged material placed in the site. Monitoring wells in the berm as described above represent the most reliable approach for detecting contaminant fluxes from the CDF to surface waters. Ecosystem impacts may be monitored by observations of contaminant uptake in plants and animals that populate the site. Air monitoring should not be necessary for a nearshore CDF, since the volatilization pathway is minimized by ponded water over the contaminated sediments.

Conceptual Design for Nearshore CDF: Overview

The nearshore CDF will be constructed at an in-water site connected to the shoreline. Two alternative dredged material volumes of 380,00 cu m (500,000 cu yd) and 1,500,000 cu m (2,000,000 cu yd) will be considered based on recommendations of the MUDS Interagency Study Team. Either site will be filled over a 10-year period. Contaminated sediment will be excavated for various projects in Puget Sound using conventional mechanical technologies such as clamshell buckets. Dredged material will be transported to the site by barge or scow. The barges will be moored at various points adjacent to the CDF dikes for transfer of material over the dikes and into the CDF. Once the design elevation for contaminated sediment is reached, clean dredged material will be placed on top of the contaminated material as a cap.

Storage Capacity and Site Geometry

The conceptual design for the nearshore CDF is based on a placement requirement for the two alternative dredged material volumes of 380,000 and 1,500,00 cu m (500,000 and 2,000,000 cu yd). A rectangular geometry was assumed for the conceptual design, however, a semicircular or other curved geometry may also be considered. Nominal dimensions for sites with these capacities are presented in Table 5.

Table 5
Dike Elevations and Dimensions for Nearshore CDFs

Feature	CDF Volume (Filled to MHHW), cu yd 500,000	CDF Volume (Filled to MHHW), cu yd 2,000,000
Elevation below MLLW	-33	-33
Elevation, MLLW	0	0
Elevation, MLW	+ 3	+ 3
Elevation, MTL	+ 7	+ 7
Elevation, MHW	+ 10	+ 10
Elevation, MHHW	+ 12	+ 12
Elevation, top of dike	+ 17	+ 17
Contaminated dredged material fill (MTL)	40	40
Side slopes (interior & exterior) H:V	2:1	2:1
Crown width, top of dike	15	15
Interior dimensions at MHHW (LxW)	1,000x500	1,800x900
Exterior dimensions at dike toe (LxW)	1,250x650	2,050x1,050
Footprint surface area	18	48
Elevation of notch for 46-m- (150-ft-) wide barge entrance (if used)	(-)5	(-)5

Note: To convert cubic yards to cubic meters, multiply by 0.7645549; acres to square meters, multiply by 4046.8

These dimensions are based on assumptions that the site bottom is flat and that the shoreline side slope is 2:1. The dredged material volume accommodated by this facility considers no net reduction due to consolidation; however, long-term consolidation would reduce the volume to some extent. Laboratory consolidation testing and modeling can be used to predict the consolidation rate and to estimate additional capacity provided by consolidation. The configuration of such a nearshore site is illustrated in Figure 15. The main

retaining dike would be constructed of select fill with a general cross section as shown in the figure.

Hydraulic dredging or unloading material will add several volumes of water for each volume of in situ sediment excavated. The dredged material slurry would undergo zone settling to approximately 140 to 200 percent of the initial in situ volume within a few days. Provisions must be made to accommodate the initial bulking and effluent discharge. Over the course of a year or more after hydraulic filling, most of the primary consolidation should occur reducing the CDF volume to near the in situ volume. Surface area for initial storage and for solids retention should be adequate since the site is large for the amount of material placed there in a 1- to 2-year time period. Settling tests for typical materials hydraulically placed should be performed for any site-specific design to verify that there is in fact sufficient surface area for a proposed site, particularly when filling above MHHW.

Containment Dikes

The conceptual design for the nearshore dike is based on nearshore site conditions in the Puget Sound area and a relatively straight shoreline configuration. The site is connected to the shoreline with the shore forming one side of the facility. The shoreline elevation assumed the conceptual design decreases from the water's edge at a slope of 2:1, or steeper. Flatter shoreline slopes will reduce depth and volumetric capacity for at least part of the site and increase the length of the dikes and the footprint for the facility.

Puget Sound has mixed semidiurnal tides, with two unequal highs and lows every 25 hr. The mean tidal range, the difference between the average high (MHW) and low (MLW), ranges from 1.6 m (5.1 ft) in Bellingham to 2.5 m (8.3 ft) in Olympia. The average maximum daily tidal range, i.e., the difference between mean low low water (MLLW) and MHHW ranges from 2.6 m (8.5 ft) in Bellingham to 4.3 m (14.6 ft) in Olympia.[1] MTL is defined as a plane midway between MLW and MHW referenced to MLLW. MTL is recommended as the maximum elevation for placement of contaminated material to ensure that it remains saturated. A site-specific design would consider the mean groundwater elevation intertidally affected by the nearshore environment. This conceptual design is based on an MTL of 2 m (7 ft) referenced to MLLW as the depth of contaminated dredged material fill for a site with a bottom elevation of 10 m (33 ft) below MLLW. The MHHW elevation is assumed to be 3.7 m (12 ft) above MLLW. An additional 1.5 m (5 ft) free board is added to make the top of the berm 5 m (17 ft) above MLLW. Therefore total dike height is 15 m (50 ft), and the depth of contaminated sediment is 12 m (40 ft).

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[1] Personal Communication. 25 March 1998: letter to Steve Babcock. U.S. Army Engineer District. Seattle. from Eric D. Johnson. Washington Public Ports Association.

A number of nearshore CDF dikes have been designed and/or constructed in the Puget Sound region. Typical Puget Sound designs are shown in Figure 16, and these designs were reviewed and considered for this conceptual design. A cross section of the nearshore dike developed for the conceptual design is shown in Figure 17. The width of the berm at the top of the dike is approximately 4.6 m (15 ft). Additional width may be considered for this long-term site to allow ease of access, increase safety factor, and to reduce long-term maintenance. Fill for the dikes is assumed to be a relatively coarse-grained commercial fill material. Side slopes for the dikes were assumed to be 2:1 for all exterior dikes. Use of dredged material for the dike fill would require much flatter side slopes. A geotechnical analysis for the specific dike height and material type will be required for a specific site. A gradual external slope (10:1 or less) would be beneficial to fish and wildlife by increasing the amount of shallow subtidal and intertidal habitat compared to steeper dike slope designs.

Exterior of the dikes should be protective against wave erosion using rip rap. The rip rap would be size-graded stones placed on the exterior dike face to a thickness of 0.9 m (3 ft). The inner dike face will be armored by 0.5 m (1.5 ft) of quarry run stones (spalls). Bank protection will be placed concurrently with dike construction.

Transport and Placement

The transport method used for the conceptual design is barge transport to moorings at various points along the dike. A crane and clamshell or dragline bucket will grab the dredged material from the barge, move it across the dike, and place it into the CDF. The crane may move along the dike or be mounted on a barge. Dolphins should be constructed at various points around the dike perimeter to allow for spreading dredged material to use the entire volume and avoid mounding at one point. Precautions against spillage during the transfer operations should be considered. Chutes extending out to the barge and over the dike would reduce losses to surface water due to spillage from the bucket.

An alternative placement method involves constructing a notch in the dike through which barges can enter the CDF and dump the dredged material directly. The dike notch could be constructed at 1.5 m (5 ft) below MLLW. When the fill elevation reaches this level, closing of the notch will commence. Barge access can continue above this elevation, perhaps to within 2.4 m (8 ft) of MHHW, by working with the tides and by using shallow draft barges. Once barge access is no longer available, material can be placed in the site by mooring the barges at dolphins or a pier adjacent to the dike and mechanically or hydraulically unloading the barges. Using a bucket, material can be moved across the dike and placed directly in the site with a crane, placed in a chute that will allow the mud to flow into the CDF, or placed on a belt conveyor for transfer into the CDF. Hydraulic placement is an option for nearby dredging projects that use hydraulic pipeline dredges, for pumpout from a barge, or for pumpout of a hopper dredge. To accommodate these optional techniques, mooring points should be

constructed in the waterway near the CDF. Pumpout options should require the dredge transporter to provide the pumping equipment needed to slurry the material and pump it from the barge to the CDF. Diameter of the pipe is expected to be 305 to 610 mm (12 to 24 in.). The inlet pipe should empty into the CDF at a point farthest from the outlet.

Operation and Management

Dredged material should be placed in the CDF so that the material spreads over the entire surface area available for storage. During the early years of the facility, natural slumping will avoid mounds of solids above the MTL. However, as the fill elevation approaches the design elevation, some buildup near unloading points is possible. A layer of water should be maintained above contaminated sediment to reduce volatile losses. An outflow structure should be placed in the dike to allow for drainage of the excess water accumulated during storm surges above MHHW and for removal of storm water during and after placement of the cap. The outflow structure consists of an adjustable weir for release of effluent or storm water to surface waters.

Figure 15 shows the alternative notched dike, single outflow structure and optional influent pipelines. The notched dike will allow for movement of tidal flows in and out of the CDF. A turbidity curtain should be selected to close the notch while unloading barges inside the CDF. This curtain would potentially enhance retention of suspended particulate and associated contaminants. The curtain must allow for passage of tidal flows over, around, or through the curtain. This concept was demonstrated in Puget Sound for the Pier 91 project.

A permeable curtain constructed of a geotextile fabric that provides for limited filtration of solids and covering the depth of the water column is sometimes used. However, because of the tidal fluctuations (up to 5.5 m (18 ft)), this type of curtain may present operational problems, does not retain clay particles, and may release trapped sediment as it rises and falls with the tide.

An impermeable fabric covering the lower part of the water column may be more effective in retaining CDF solids, particularly the more concentrated plume. A mechanism for lowering, or pulling back, the curtain during barge passage should be developed during the site-specific design. A second curtain could be employed for the upper part of the water column to force suspended sediment to the lower part of the water column. Another alternative is to use a curtain inside the CDF to surround the barge during dumping and encourage flow of suspended sediment to the bottom of the CDF. Provisions for opening the curtain to allow barge entrance and exit would be required.

During the later stages of filling, when the notch is closed and as the contaminated material fill rises to the MHW elevation, the site should be managed for a minimum of 0.6 m (2 ft) of ponding during the placement of dredged material in the site to allow for settling of suspended solids during hydraulic filling and storm water runoff.

Contaminant Control Measures

No contaminant pathway testing was performed during this phase of the MUDS study. Therefore, the conceptual design did not specifically address potential design requirements for additional controls to reduce contaminant losses by specific pathways. It should be noted that while the testing cannot be done for the conceptual design, pathway testing is recommended for any site-specific design.

Contaminant control measures assumed for the nearshore conceptual design are focused on potential diversion of groundwater inflow and a surface cover for closure. Leachate movement through the bottom of the site is generally not a concern for nearshore sites because of the limited permeability of the dredged material small differences in hydrostatic head. Tidal dispersion of contaminants as water moves through the dike between high and low tides is a major pathway of concern. As stated previously, monitoring and modeling results for such sites in Puget Sound suggest that physical, chemical, and biological processes promote attenuation of contaminants within the dike. Volatilization is of little or no concern for the nearshore site if contaminated materials are placed only below the MHW elevation. The volatilization, surface runoff, and plant and animal uptake will be controlled after site closure by covering the contaminated dredged material with clean dredged material or soil.

Following final placement of contaminated material, time should be allowed for consolidation prior to closure. Once the cover layer is raised above MHW, the excess water can be decanted and the cover allowed to drain and desiccate. The final cover will be a clean material with a thickness of at least 0.6 m (2 ft). A topsoil layer or pavement can be placed once the cover has sufficiently dried for movement of low-ground-pressure equipment. If consolidation of the underlying materials is sufficiently large, a second placement of clean cover material may be necessary at a future date to maintain the surface above MHW elevation.

An optional final cover design is to limit the cover elevation to a few meters (feet) below MHW and provide for intertidal flow in the CDF. The resulting intertidal surface area would benefit fish and wildlife provided the risk of contaminant exposure is determined to be low.

Design and Performance Standards for Nearshore CDFs

This section provides narrative and, where appropriate, numerical design and performance standards for the MUDS nearshore CDF option. The proposed standards are intended to be applied to a site-specific design should a nearshore CDF option be selected for MUDS. The standards are based on available technical guidance in the literature, as well as available design information from

projects nationwide and within Puget Sound. The standards for various aspects of the design are stated in the following text, and all the proposed standards are summarized in Table 6.

Overall objectives for nearshore CDF option. An overall design objective for nearshore CDFs is to provide sufficient diked volumetric capacity to accommodate the required volume of dredged material and contain the dredged material such that any releases of contaminants from the site will be within acceptable limits.

Engineering design procedures. The site design will be completed by competent professional engineers, and standard USACE engineering design documents will be applied as appropriate in the design. A listing of USACE Engineer Manuals and other design documents is given in EP-25-1-1 (HQDOA 1995b).

Environmental evaluations and contaminant pathway controls. Environmental evaluations conducted as a part of the design will be in accordance with the Technical Framework (USACE/EPA 1992) and other applicable state and local guidelines.

Open dike configuration for bottom dump operation. During any phase of operation with a dike opening, the nearshore CDF must be operated to control direct exposure of offsite organisms to the contaminated sediments such that toxicity or unacceptable levels of bioaccumulation do not occur.

Dike height. The constructed dike height for the nearshore CDF will be determined considering capacity requirements, surface area requirements, initial water depth, tidal fluctuations, wave height and storm surge for a design storm event, and the anticipated end use of the site, once filled. Assuming a design project life of 50 years, the minimum design storm that should be considered is a storm having a 73-year return period.

Retaining dike stability. Nearshore retaining dikes are complex major structures requiring all pertinent aspects of formal geotechnical design. Depending on the design alternatives, sliding, overturning as well as slope instability must be thoroughly investigated. Soft foundation conditions can lead to shear failures in the foundation as well as erosion at the toe of the structure. Wave dynamic loading generally affects armor stability but can also lead to pressure differential within the structure and in the foundation. Other loadings of concern may be earthquake loads, or even the active and passive soil pressures in the confined material itself pushing outward on the dike, especially if the structure is filled to near crest elevations.

The stability of the structure must be addressed from both static and dynamic points of view. Dynamic loadings may be either seismic (earthquake) or the result of storm surge waves. If the containment structure is fundamentally a dike of rock or soils, design will primarily fall to the geotechnical engineer. If the structure is of any other configuration such as coffer cells, concrete caissons, or

Table 6
Design and Performance Criteria for Nearshore CDFs

Item or Category	Performance Criterion
Overall design objective	Provide sufficient capacity; contain the dredged material so that any releases of contaminants from the site will be within acceptable limits.
Site characteristics	Equipment access to the disposal site must be available.
Engineering design	Standard USACE engineering design documents and local Puget Sound experience applied as appropriate.
Environmental evaluations	Sites evaluated in accordance with the USACE/EPA (1992) Technical Framework and other applicable guidelines.
Operation with a dike opening	Operated to control direct exposure of organisms as for an excavated CAD pit.
Dike height	Determined considering capacity requirements, surface area requirements, initial water depth, tidal fluctuations, wave height and storm surge for a design storm event, anticipated end-use of the site, once filled.
Dike stability	Dike of the coffercell type must meet a safety factor of 1.1 to 1.5 against sliding and 1.0 to 3.0 against bearing failure, depending on the specific loading condition; dike of the embankment type must meet a safety factor of 1.0 to 1.5 against slope failure, depending on the loading condition; design must meet a safety factor of 1.5 against liquefaction of the embankment and/or foundation; bed materials and the depth of material layers must be investigated; confine sediment and avoid dike failure; accepted geotechnical and earthwork engineering methods used; structural strength and erosion protection will be incorporated in the design.
Erosion protection	Armor designed to resist changes in the armor stone profile or displacement of armor units under the design storm.
Excavated material	Dredged, transported, and placed in accordance with the proper disposal or use criteria of the materials excavated.
Dredging and Placement/Offloading	Provisions to contain spillage and leakage from bucket; pumpout facilities to accommodate solids retention and minimize spillage and leakage; contaminated sediments dredged by a hydraulic pipeline dredge with direct pipeline placement; submerged pipeline 183- to 305-m- (600- to 1,000-ft-) long required in navigation areas; maximum of two booster pumps in line; minimum 0.305-m (1-ft) over depth of clean sediments.
Outlet (weir) structures	Sized to pass 25-year rainfall event plus flow rate for offloading; drop inlet sluice-style outlets with fixed length and variable height overflow; entrance drop box to the outlet structure with a weir length that limits overflow depths to 51 to 102 mm (2 to 4 in.).
Site operations/ sequencing	As scheduling will allow, initially, materials placed with lower potential for adverse impact ; all contaminated sediments placed below the mean tide water elevation; contaminated sediments placed to remain anaerobic and wet for the long term.
Solids retention	Maintained to ensure that standards for particulate-bound contaminants, TSS, or turbidity are met at the boundary of the designated mixing zone; sufficient dike height and surface area to retain sediments during dredging disposal and during subsequent consolidation and dewatering of sediments; effluent quality release for hydraulic filling less than 100 mg/L using EM 1110-2-5027 (HQDOA 1987) procedures; discharge managed to provide maximum hydraulic efficiency for settling.
Effluent quality	Dissolved contaminant concentrations not to exceed applicable acute water quality standards and concentrations of suspended dredged material not to exceed applicable water column toxicity criteria at the boundary of the designated mixing zone; control measures required when permit requirements are exceeded.
Leachate quality	Dissolved leachate contaminant concentrations not to exceed applicable chronic water quality standards nor applicable water column toxicity criteria at the boundary of the designated mixing zone; all contaminated sediments placed below groundwater/tidal elevations; no impermeable liner or core required based on premise that the contaminated material will be less permeable than the dike material.

(Continued)

Table 6 (Concluded)	
Item or Category	**Performance Criterion**
Direct uptake	Silt screen, wire mesh screen, or other fish passage barrier will be maintained across the dike notch (if used).
Volatilization	Site operated and managed such that measured air concentrations do not exceed applicable air quality standards.
Dewatering	Volumetric disposal capacity maximized to the greatest extent feasible.
Final cover	Designed to control surface runoff and direct uptake by plants and animals; design to include primary and a final cover; primary cover placed in thin lifts while sediments are still wet; final cover placed following initial consolidation; final cover is engineered design appropriate for future site use, e.g., site vegetation, armoring with larger grain-size sediments, or paving.

a combination including soils or rock, stability analyses will typically involve both structural and geotechnical engineers. Where coffercell or concrete structures are to be used, the structural engineer selects a design configuration which is stable against sliding and overturning. The geotechnical engineer then assesses that concept for foundation bearing capacity, static and dynamic stability, including the foundation, and for settlement.

Guidance for design practice and required factors of safety which are probably most pertinent to nearshore or upland retention structures is found in the following USACE Engineer Manuals:

- EM 1110-2-2502, "Retaining and Flood Walls" (HQDOA 1989).
- EM 1110-2-1902, "Stability of Earth and Rock-Fill Dams" (HQDOA 1970a) (Revision of this EM is nearing completion under the new and more general title, "Shear Strength and Slope Stability").
- EM 1110-1-1904, "Settlement Analysis" (HQDOA 1990).
- Engineering Regulation ER 1110-2-1806, "Earthquake Design and Evaluation for Civil Works Projects" (HQDOA 1995a).

Static stability. EM 1110-2-1902 (HQDOA 1970a) provides minimum factors of safety for all cases where the structure is an earthen embankment and other types of structures where stability checks must be made against failure through the foundation soils. In accordance with these criteria, the design of a dike of the coffer cell type must meet a safety factor of 1.1 to 1.5 against sliding and 1.0 to 3.0 against bearing failure, depending on the specific loading condition. The design of a dike of the embankment type will meet a safety factor of 1.0 to 1.5 against slope failure, depending on the loading condition.

Dynamic stability. Earthquake design criteria are not yet formalized in a USACE Engineer Manual. Earthquake considerations are a specialty concern within geotechnical engineering and require the input of the appropriate regional experts with respect to the establishment of the design earthquake to the analyses of its effects. Where dynamic loadings to the foundation deriving from storm

waves are concerned, no formal stability criteria currently exist for offshore structures. Wave loadings can induce pore pressure increases and consequent shear strength losses in the foundation soils. The extreme of such an effect is actual liquefaction of the materials if they are of sufficiently low plasticity and cohesion. Therefore, whether the dynamic loading is seismic or wave-induced, safe design is not a conventional procedure and must be addressed by the qualified specialists.

A sequence of steps should be followed in evaluating ground motions and performing seismic analyses for earth, concrete, and steel structures (after Krinitzsky, Hynes, and Franklin 1996, revised by Krinitzsky 1997). These steps, as applied to containment dikes, are as follows:

a. *Determine level of criticality.* What is the required safety margin? What is the allowable level of damage? Are the consequences of failure intolerable - fatalities, economic, and environmental losses?

b. *Determine earthquake category.* If the structure is critical (intolerable consequences of failure defined as breaching of dike and significant flow or release of contained sediments), then the DBE should be the MCE determined from a site-specific evaluation of seismic sources, maximum possible magnitudes, and attenuation over the closest distance to the site of mean-plus-one-sigma motions. If the structure is less than critical, then the DBE should be selected as an RCE based on all the information determined for the MCE plus a probabilistic seismic hazard analysis incorporating the frequency of earthquake occurrence and an assessment of consequences of failure.

c. *Evaluate seismic hazard.* Identify seismic sources that could affect the site; establish maximum credible events for each source and historical seismic activity; establish DBE as MCE or perform risk analysis to determine RCE; attenuate DBE motion from each controlling source to the site to determine peak ground motions parameters and response spectra for analysis.

d. *Determine foundation conditions and liquefaction susceptibility.* In addition to the usual foundation investigation for static loads, determine shear wave velocity profiles, perform CPTs and/or SPTs according to liquefaction evaluation requirements. Collect samples to determine gradations, fines contents (percent passing the number 200 sieve), plasticity of fines, water content, and in situ density. For cohesionless materials, determine relative density of foundation soils. Evaluate liquefaction susceptibility using DBE motions, and determine areal extent, thickness, and depth of liquefiable materials. Evaluate liquefaction potential and stability of shore abutment for fill and dikes.

e. *Design dike for combined static and seismic loads.* Design dike materials to be nonliquefiable for the DBE (for example, use compacted, rolled fill for upland dikes and clean rock fill with a flexible core and filter system,

possibly with geosynthetics, for nearshore dikes). If liquefiable materials are present in the foundation, assign residual strengths to them and evaluate design alternatives. If liquefiable materials are present over a large area, they may need to be removed or improved. Experience in California indicates that hydraulically placed materials generally do not liquefy at peak acceleration levels less than 0.15g for earthquakes with magnitudes of 6 or less. (A difficulty with probabilistically determined DBE motions is that magnitude levels are obscured.) If the DBE motions are less than this threshold event, then the dredged fill might not liquefy and some level of shear strength could be assumed for the contained fill. If the DBE motions are equal to or more severe than this event, assume that the contained fill has no shear strength and imposes a heavy fluid load on the dike, and may include hydrodynamic effects. Analyze pseudo-static slope stability and translation (determine yield accelerations for these failure modes), potential Newmark-sliding block movement, bearing capacity, and settlement of the dike. Several feet of outward movement and/or settlement of the dike may be acceptable if defensive measures are incorporated in the dike design and repairs, if needed, can be constructed in a timely manner after the earthquake.

Erosion protection

Dike features associated with resistance to wave erosion will be a major influence on the selection of the type of dike (cellular structure vs rubble mound, etc.) and the overall design. Design of the dike for erosion protection will follow available guidance in the Shore Protection Manual (1984) and Bruun (1989).

The selection of design wave height (discussed previously), wave period, and storm surge has a significant effect on the final structural design. A key factor in the structural design of armored retaining dikes (concrete or stone) is the hydraulic stability of the primary armor layer, a function of wave height.

Specific safety factors are not normally used in armor stability design. The question of allowable movement and safety factor with respect to armor design must be based on an acceptable degree of damage for the design storm event. For purposes of preliminary design, the Hudson equation is normally used to determine stone size. A model study is recommended for the final design. The armor will be designed to resist significant changes in the armor stone profile or displacement of armor units under the design storm.

Dredging and placement methods/offloading facilities for contaminated sediments

Most of the site will be filled by bucket transfer from a barge or scow to the CDF. Multiple mooring points will be provided to allow for unloading at various points around the dike perimeter.

An option for the later stages of filling could include hydraulic offloading from barges or hopper dredges. Many hopper dredges are equipped with onboard pumpout capability, and these dredges could hydraulically offload directly into the CDF. A mooring dock with appropriate landside pipelines over the dike to selected inflow points will be required. For barge offloading, a special offloading facility will be needed. Such a facility has been used at the Hart Miller Nearshore or upland site near Baltimore. A hydraulic offloader with a 610-mm (24-in.) main pump capable of discharging 1,900 cu m (2,500 cu yd) per hour through lines of up to 5,486 m (18,000 ft) was also used for the Sonoma Baylands project in San Francisco Bay (World Dredging Mining and Construction 1996). Such offloading facilities consist of an offloader which is essentially a specially configured hydraulic pipeline dredge. The offloader head is equipped with water jets to introduce slurry water into the barge to allow for pumping of the relatively lowwater content material resulting from mechanical dredging. Offloading pumpout facilities will be sized to offload barges, with flow rate matched with available ponded surface area to accommodate solids retention requirements.

Spillage and leakage are concerns for bucket transfer over the dike and for hydraulic offloading facilities involving pipelines. Special controls for hydraulic systems, such as hydraulic checks, should be considered to prevent significant spills in the even of a pipeline break. Offloading facilities will have appropriate provisions to minimize spillage and leakage.

Weir structures

Weir structures will be required to allow discharge of the excess entering the CDF though dredged material addition, storm water or storm surge over the dike. Weir structures will be sized to pass a design discharge consisting of rainfall runoff for a 25-year rainfall event plus flow rate for the largest offloading pump. If multiple weir locations are selected for purposes of site management, each of the structures should be sized to pass the design effluent discharge flow rate. The CDF should also be designed to accommodate an emergency drawdown of ponded water if required.

Fill height/sequencing

Although a detailed site operations plan will be required and must be based on the specific configuration and conditions for the selected site, some preliminary site operation principles with respect to fill height and sequencing

can be considered. The final fill height must account for a final cover of clean material (see discussion below regarding final closure).

If scheduling of dredging projects will allow, materials with lower potential for adverse impact should be placed in the CDF in the initial stages of filling. This would provide a layer of clean materials against the base of the dike and bottom of the CDF to act as an ad hoc liner to retard and attenuate leachate from later placement of more contaminated materials. All contaminated material will be placed in the nearshore CDF at elevations below the MTL elevation to ensure that the sediments remain in a saturated and anaerobic condition. Once contaminated material reaches the MTL, a clean sediment cap will be added.

Suspended solids retention

A CDF must be designed and operated to provide adequate initial storage volume and surface area to retain suspended solids such that clarified water is released or discharged. A mechanically filled site will have minimal flow over the weir because of the small rate of volume increase after the dredged material placement. Suspended solids that remain in the water column will be filtered by flow through the dikes.

For operations involving placement by barge using a notch in the dike, the retention of solids is dependent on the degree of water column dispersion during placement. Use of clamshell dredges and placement by bottom-dump barges should minimize dispersion. The dispersion can be controlled by the scheduling and frequency of placement, limits on the size of barges used, and the use of a silt curtain or other barrier across the dike notch. The barge placement operation will be controlled such that applicable water quality standards for TSS or turbidity are met at the boundary of the designated mixing zone.

For hydraulic filling, the required ponded surface area and ponded water depth is governed by the settling behavior of the fine-grained sediments placed in the site. Adequate ponded surface area and water depth will be maintained during hydraulic filling operations to ensure that applicable water quality standards for TSS or turbidity are met at the boundary of the designated mixing zone. Procedures for sizing the required ponded area and depth described in EM 1110-2-5027 (HQDOA 1987) should be followed.

Contaminant Release Pathways

A CDF for contaminated sediments must be designed to contain dredged material within the site and restrict contaminant mobility out of the site to control or minimize potential environmental impacts. Several possible mechanisms or pathways for transport of contaminants from a CDF should be considered:

a. Contaminant transport via tidal dispersion through the dikes.

b. Surface runoff of contaminants due to precipitation.

c. Leaching into groundwater.

d. Uptake by plants or animals directly from sediments, or by indirect animal uptake from feeding on vegetation.

e. Gaseous or volatile emissions during and after placement of dredged material.

Each of these potential pathways will require consideration of specific design or performance standards.

Effluent quality

Effluent is the discharge or release of water during active filling operations. Effluent is considered a dredged material discharge under Section 404 of the CWA. State water quality certification will determine any standards that must be met. The site will be designed and operated such that dissolved effluent contaminant concentrations will not exceed applicable acute water quality standards at the boundary of the designated mixing zone. Further, the effluent will not exceed applicable water column toxicity criteria at the boundary of the designated mixing zone.

Surface runoff

The MUDS nearshore option calls for all contaminated dredged material to be placed at or below the MTL. There will be no potential for drainage and exposure of a contaminated site surface to precipitation, and therefore no design or performance standards relating to surface runoff are required.

Groundwater leachate and dike seepage

Leachate refers to water that passes through dredged material in a CDF and flows into groundwater beneath the site or through the dikes. From a regulatory standpoint, leachate may fall under the 401 Water Quality Certification or considered as a part of the NEPA process. The site will be designed and operated such that dissolved leachate or tidal flow contaminant concentrations will not exceed applicable chronic water quality standards at the boundary of the designated mixing zone. Further, leachate discharge will not exceed applicable water column toxicity criteria at the boundary of the designated mixing zone.

Direct uptake

Since all contaminated dredged material will be placed at or below the MTL, there will be no potential for colonization of the site by terrestrial plants and animals. However, avian impacts must be assessed. The contaminated materials placed in the nearshore site below the MTL will become temporarily colonized by aquatic benthic organisms. These organisms would potentially bioaccumulate contaminants to unacceptable levels, and subsequent movement into the aquatic food chain is possible. Interim subaqueous caps could be considered as a control, similar to the approach for a contained aquatic disposal (CAD) option.

Volatilization

Volatilization of contaminants directly from sediment with overlying water to air is only a potential concern for sediments with relatively high levels of volatile organics. Air quality criteria may be considered as a part of the NEPA/SEPA process. The site will be operated and managed such that measured air concentrations do not exceed applicable air quality standards.

Final cover

Once the dredged material fill has reached its limiting height in the CDF, appropriate management and other control measures should be considered to allow for long-term site use. Physical isolation of the material to prevent direct human contact and uptake by organisms colonizing the site by placement of a surface cover would be the most efficient means. A layer of suitable material will be placed to act as a final surface cover. The cover design, to include thickness and composition of the layer, will provide an effective control for the surface runoff and direct uptake pathways for plants or animals.

Since a nearshore MUDS site will likely be developed once filled, the intended end use of the site may dictate other structural requirements for the cover design. The surface cover will include a primary and a final cover. The primary cover will be placed in thin lifts while sediments are still wet. The final cover will be placed following initial consolidation and will require an engineered design appropriate for future site use, e.g., site vegetation, armoring with larger-grain-size sediments, or paving (Parametrix, Inc. 1990).

4 Level Bottom Capping and Contained Aquatic Disposal

Description, Definitions, and Application

Capping is the controlled placement of contaminated material at an open water site followed by a covering or cap of clean isolating material. Capping is a control measure for the benthic contaminant pathway. Level bottom capping is a term used for capping without means of lateral containment. If some form of lateral containment is used in conjunction with the cap, the term contained aquatic disposal is used. Considerations in evaluating the feasibility of capping include site bathymetry, water depth, currents, wave climate, physical characteristics of contaminated and capping sediments, and placement equipment and techniques. Because long-term stability of the cap is of concern, capping is generally considered to be more technically feasible in low-energy environments. Precise placement of material is necessary for effective capping, and use of other control measures such as submerged discharge and lateral containment increase the effectiveness of capping. Guidelines are available for planning and design of capping projects (Truitt 1987a,b; Palermo 1991a,b,c; Palermo, Fredette, and Randall 1992; Palermo, Maynord, Miller, and Reible 1996; and Palermo et al. 1998).

Level bottom capping (LBC) is defined as the placement of a contaminated material in a mounded configuration and the subsequent covering of the mound with clean sediment. CAD is similar to LBC but with the additional provision of some form of lateral confinement (e.g., placement in bottom depressions, or behind subaqueous berms) to minimize spread of the materials on the bottom. An illustration of LBC and CAD is shown in Figure 18.

The objective of LBC is to place a discrete mound of contaminated material on an existing flat or very gently sloping natural bottom. A cap is then applied over the mound by one of several techniques, but usually in a series of disposal sequences to ensure adequate coverage.

CAD is generally used where the mechanical properties of the contaminated material and/or bottom conditions (e.g., slopes) require positive lateral control measures during placement. Use of CAD can also reduce the required quantity of cap material and thus the costs. Options might include the use of an existing natural or excavated depression; preexcavation of a disposal pit; or construction of one or more submerged dikes for confinement (Palermo 1991a; Truitt 1987a).

Capping applications

Subaqueous borrow pits provide an ideal configuration for CAD. Such pits could be previously excavated and left following sand or gravel mining operations or excavations for other purposes or could be excavated as constructed CAD pits solely for the purpose of providing capacity for dredged material disposal (Palermo 1997). CAD in large borrow pits has been implemented in Hong Kong. Borrow pit CAD has also been implemented in Los Angeles, Portland, New York, and Rotterdam Harbor.

In Hong Kong, the East Sha Chau marine borrow pits are being used for placement of sediments deemed unsuitable for conventional ocean disposal (ERM 1996). The East Sha Chau pits are constructed pits, i.e., sited and designed so that the material excavated to form the pit is used for a beneficial purpose and the pit itself is used for disposal of contaminated dredge material. The borrow pits were created by sand dredging undertaken by the Airport Authority and are located to the north of Chek Lap Kok Airport and Lantau Island. Three series of pits have already been filled and capped and a fourth series is now under design. These pits were excavated by hopper dredges, and the excavated materials placed for the airport fill. Contaminated sediments were dredged and placed in the excavated pits by surface release from hoppers and barges. Layers of clean sediments were also dredged and placed by hoppers and barges as the cap.

In Los Angeles, a pit previously excavated for island construction has been used for placement of contaminated sediment dredged from the Los Angeles River, and another pit site is now under study for further use for CAD. In Portland, an excavated gravel pit within an island in the Columbia River has been used for CAD of contaminated sediments from the Portland Harbor area. Existing borrow pits have been considered for CAD at the Port Authority of New York and New Jersey (PANYNJ) (USAE District, New York 1991, 1992, and 1996) and in San Francisco Bay (USACE District, San Francisco and Port of Oakland 1994). A 1.5 million-cu yd CAD has been constructed by PANYNJ in Newark Bay and operations began in 1997 (SAIC in preparation).

Application of capping in Puget Sound

Capping has been used in several navigation and contaminated sediment remediation projects in Puget Sound. In fact, the first CAD project executed in the United States was located in the Duwamish River, and much of the field

experience gained in the United States for shallow in situ capping has been gained at sites in Puget Sound.

Contaminant Pathways

The contaminant pathways of concern for level bottom capping and CAD are the same as for open water placement without capping: water column and benthic. The water column pathway refers to the potential release of contaminants to the water column during payment of material prior to capping. The benthic pathway refers to the potential toxicity or bioaccumulation of contaminants to benthic organisms which will recolonize the site. Capping is a control measure for the benthic pathway and must be designed to effectively control that pathway.

Processes and Design Considerations

Capping is a contaminant control measure to prevent impacts. However, dredged material capping requires initial placement of a contaminated material at an open water site. There are several issues which therefore must be carefully considered within the context of a capping project design. These include:

a. *Potential water column impacts during placement.* Assessment should consider evaluation of potential release of contaminants to the water column, evaluation of potential water column toxicity, and evaluation of initial mixing. Elutriate test procedures for water quality, water column bioassay tests, and computer models for dispersion and mixing are available to address these requirements. The mass loss of contaminants during placement (fraction dispersed offsite and remaining uncapped) may also be predicted using these same tests and models.

b. *Efficacy of cap placement.* Assessment should consider available capping materials, methods for dredging and placement of both contaminated material and cap material, and compatibility of site conditions, material physical properties, and dredging and placement techniques. Guidance on selection of appropriate methods, compatibility with site conditions and material properties, and computer models for predicting mound development and spreading behavior are available.

c. *Long-term cap integrity.* Assessment should consider the physical isolation of contaminants, potential bioturbation of the cap by benthos, consolidation of the sediments, long-term contaminant losses due to advection/ diffusion, and potential for physical disturbance or erosion of the cap by currents, waves, and other forces such as anchors, ship traffic, etc. Test procedures for contaminant isolation and consolidation and

computer models for evaluation of long-term contaminant diffusion and resistance to erosion are available.

Design Requirements

Each of these issues must be appropriately addressed by the project design. More detailed discussion of these processes and design considerations is given in the following paragraphs.

Viability of capping as an alternative

Capping is only one of several alternatives which may be considered for dredged material which is contaminated and would require isolation from the benthic environment if proposed for open water disposal. If the issues just described can be satisfactorily addressed in the project design for the specific set of sediment, site, and operational conditions under consideration, capping is a technically viable option.

Capping is not a technically viable option for a specific set of sediment, site, and operational conditions when:

a. The contaminant release and dispersion behavior of the contaminated material (even with consideration of controls) result in unacceptable water column impacts during placement.

b. The spreading or mounding behavior of the contaminated material or cap material (even with consideration of controls) indicate that the required cap cannot be effectively placed.

c. The energy conditions or operational conditions at the site are such that the required cap thickness cannot be effectively maintained in the long term.

d. The institutional constraints do not provide the ability to commit to the long-term monitoring and management requirements.

Under such circumstances, other options for disposal of the contaminated sediments must be considered.

Design philosophy for capping

Capping must not be viewed merely as a form of unrestricted open water placement. A capping operation is treated as an engineered project with carefully considered design, construction, and monitoring to ensure that the design is adequate. The basic criteria for a successful capping operation are that

the cap thickness required to isolate the contaminated material from the environment be successfully placed and maintained.

Design requirements

The design requirements for an LBC or a CAD project include characterization of both contaminated and capping sediments, selection of an appropriate site, selection of compatible equipment and placement techniques, prediction of mixing and dispersion during placement, determination of the required capping sediment thickness, prediction of material spread and mounding during placement, evaluation of cap stability against erosion and bioturbation, and development of a monitoring program (Shields and Montgomery 1984; Truitt, Clausner, and McLellan 1989; and Palermo 1991a).

There is a strong interdependence between all components of design for a capping project. For example, the initial consideration of a capping site and placement techniques for both the contaminated and capping materials strongly influence all subsequent evaluations, and these initial choices must also be compatible for a successful project (Shields and Montgomery 1984). Each step in the process must be clearly identified and documented before a decision can be made to proceed.

When an efficient sequence of activities for the design of a capping project is followed, unnecessary data collection and evaluations can be avoided. General descriptions of the various design requirements are given in the following paragraphs as they correspond to the recommended design sequence (Palermo 1991a).

Sediment Characteristics Related to Capping

Characterization of both the contaminated sediment and potential capping sediments is necessary for evaluation of the environmental acceptability of sediments for open water placement and to determine physical and engineering properties necessary for prediction of both short- and long-term behavior of the sediments. Some characterization data may have been obtained as a part of a more general investigation of disposal alternatives prior to consideration of capping.

Characterization of contaminated sediment

The contaminated sediments to be capped are likely to have been characterized to some degree prior to consideration of capping. In any event, the contaminated sediment must be characterized from physical, chemical, and biological standpoints.

Characterization/selection of capping sediment

Several sediments may be available for selection as the capping sediment to be used for a particular capping project. For economic reasons, a capping sediment is usually taken from an area which also requires dredging. If this is the case, there may be a choice between multiple dredging projects; the schedule for dredging will then be an important consideration. In other cases, removal of bottom sediments from areas adjacent to the capping site may be considered. For example, material from the Ambrose channel in New York Harbor was removed for use as capping material at the Mud Dump site. If CAD is under consideration, material removed to create CAD cells may be stockpiled and used later in the capping operation (Averett et al. 1989; Sumeri 1989). Such materials must be characterized and determined to be suitable for open water placement.

Previous studies have shown that both fine-grained materials and sandy materials can be effective capping materials. However, the physical characteristics of the capping sediment should be compatible with the contaminated sediment, considering the dredging and placement techniques used for both.

Site Selection and Evaluation

General considerations

The selection of an appropriate site is a critical requirement for any capping operation. Since the cap must provide long-term isolation of the contaminated material, capping sites should generally be characterized as nondispersive sites, where material is intended to remain in a stable deposit. Therefore, the considerations for site selection for a conventional nondispersive open water disposal site also apply to capping sites (Palermo 1991b).

The selection of a potential site for capping is subject to the same constraints and tradeoffs as any other nondispersive open water disposal site. However, beyond the normal considerations, the capping site should be in a relatively low-energy environment with little potential for erosion of the cap. While capping a low-energy site is desirable, such sites are not always available. Higher-energy sites can be considered for dredged material capping, but a detailed study of erosion potential is required, and increases in cap thickness to account for potential erosion may be required. Monitoring and maintenance costs may also be higher for higher-energy sites.

Special consideration of site bathymetry, currents, water depths, bottom sediment characteristics, and operational requirements such as distance, sea state, etc. are required in screening or selecting sites for capping (Truitt 1987a; Truitt, Clausner, and McLellan 1989).

Bathymetry

The bathymetry of the site has an influence on the degree of spread during placement of both contaminated and capping material. The flatter the bottom slope the more desirable it is for LBC projects, especially if material is to be placed by hopper dredge. If the bottom in a disposal area is not horizontal, a component of the gravity force influences the energy balance of the bottom surge (lateral movement of the disposed material as it impacts sea bottom) and density flows because of the slope following impact of the discharge with the bottom. It is difficult to estimate the effects of slope alone, since bottom roughness plays an equally important role in the mechanics of the spreading process. To date, LBC projects in which the material was mechanically dredged and released from a barge have been executed at sites with slopes up to 1:60 (Clausner et al. 1998); and in which material was placed by hopper dredge at sites with slopes up to 1:225 (i.e., New York Mud Dump site). Placement of material on steep bottom slopes (steeper than 1v on 100h) should generally be avoided for a capping project (Truitt 1987a) because of the potential for a slope adjustment in the contaminated sediment mound. Bathymetry forming a natural depression tends to confine the material, resulting in a CAD project. This is the most desirable type of site bathymetry for a capping project.

Currents

Water-column currents affect the degree of dispersion during placement and mound location with respect to the point of discharge. Of more importance are bottom currents which could potentially cause resuspension and erosion of the mound and cap. The effects of storm-induced waves on bottom current velocities must also be considered. Capping sites need to have current and wave climate characteristics which result in long-term stability of the capped mound or deposit. Collection of basic current information is necessary at prospective disposal sites to identify site-specific conditions.

Currents have a major effect on the degree of dispersion of material in the water column during placement. A vast majority of the mass of a discharge from a barge or hopper dredge (95 percent or greater) quickly descends to the bottom and is not subject to water column dispersion (Truitt 1986a). A small fraction of the material (5 percent or less) is stripped from the discharge during descent or suspended in the water column following impact of the discharge with the bottom. This fraction is subject to water-column dispersion and the effect of currents on this process must be evaluated.

Another possible influence of currents in the receiving water during placement is to displace the point of impact of the descending jet of material with the bottom (by a calculable amount). Water-column currents need not be a serious impediment to accurate placement. Further, currents do not appear to affect the spreading of material once it encounters the bottom (Bokuniewicz et al. 1978, Truitt 1986a). However, water column currents and bottom slopes

are important in slow placement of sand caps where the currents and density flows can cause some waste of capping sand.

Long-term effects of currents at a prospective site may still need to be investigated from the standpoint of potential erosion of the mound and cap or potential recontamination of the site from adjacent sources. Storm-induced currents are also of interest in the long-term stability of the site. However, disposal operations are not conducted during storms, so the designer does not need to consider storm induced currents during disposal. Measured current data can be supplemented by estimates for external events using standard techniques; for example, see the Shore Protection Manual (1984). Selection of a nondispersive site in a relatively low-energy environment normally results in a site with low bottom-current velocity and little potential for erosion. However, if the material is hydraulically placed, a thorough analysis of the potential for resuspension and erosion is necessary. Conventional methods for analysis of sediment transport can be used to evaluate erosion potential (Teeter 1988, Dortch et al. 1990). These methods can range from simple analytical techniques to numerical modeling (Scheffner 1989). In the analysis of erosion, the effects of self-armoring because of the winnowing away of finer particles should be considered. However, no models exist that predict how a specific sediment with a range of grain sizes would be winnowed.

Predicted erosion values due to currents and storm waves should be used as a criterion in screening and/or selecting sites. For projects in which no subsequent capping is anticipated (e.g., the final cap for a site) or for which materials for cap nourishment are not easily obtained, net cap erosion should not exceed 0.305 m (1 ft) over a period of 20 years of normal current/wave energies or 0.305-m (1-ft) erosion for a 100-year extreme event. For projects in which subsequent capping is planned or for which materials for cap nourishment can be easily obtained, higher erosion rates may be considered. In areas where available capping materials are limited and current and wave conditions are severe, a coarse-grained layer of material may be incorporated into the cap design to provide protection against erosive currents at the site.

Average water depths

Recent case studies have indicated that water depth is of particular interest in evaluating the potential suitability of a site for capping operations (Palermo et al. 1989), and water depth is an important consideration for Puget Sound. The deepest water depth for which a capping project has been executed (as of 1995) is approximately 61 m (200 ft) (Wiley 1996). Greater water depths generally provide more stable bottom conditions with less potential for erosion. However, the greater the average water depth at the site, the greater the potential for water entrainment and dispersion during placement. The expense and difficulty in monitoring are also increased with a greater water depth.

As water depth increases, both the contaminated and clean material must descend through a greater water column depth. More material is released to the

water column during placement as compared to shallower water placement, all other factors being equal. Therefore, the fraction of the contaminated material that is not finally capped is greater.

Entrainment of ambient water causes the descending material to become more buoyant; therefore, the effect of density stratification in the water column needs to be evaluated. Although density stratification in the water column may be encountered at some deepwater sites, stratification is not likely to prevent the descent of the dredged material mass during placement. The very cohesive fraction of mechanically dredged material (clods or clumps) attains terminal speed quickly after release from a barge and does not accelerate further with depth.

The increased water entrainment with deepwater placement may also result in a greater spread of the more fluid material on the bottom, but entrainment reduces the overall potential energy at bottom impact. Field studies indicate that the bottom surge does not spread at a faster rate than that occurring in shallower depths, although because of additional entrainment, the initial thickness of the surge a function of water depth (Bokuniewicz et al. 1978). Greater care in control of placement may therefore be required as water depth increases to develop a discrete mound of contaminated material and adequate coverage of the mound with capping material.

Operational requirements

Among the operational criteria that must be considered in evaluating potential capping sites are: site volumetric capacity, nearby obstructions or structures, haul distances, bottom shear as a result of ship traffic (in addition to natural currents), location of available cap material, and potential use of bottom drag fishing equipment. The effects of shipping are especially important, since bottom stresses, because of anchoring, propeller wash, and direct hull contact at shallow sites, are typically of a greater magnitude than the combined effects of waves and other currents (Truitt 1987a).

Equipment and Placement Techniques

Equipment and techniques applicable to placement of contaminated material to be capped and clean material used for capping include conventional discharge from barges, hopper dredges, and pipelines; diffusers and tremie approaches for submerged discharge; and spreading techniques for cap placement (Palermo 1991c).

Contaminated material dredging and placement

Placement of contaminated material for a capping project should be accomplished so that the resulting deposit can be defined by monitoring and effectively capped. Therefore, the equipment and techniques for dredging, transport, and placement must be compatible with that of the capping material. Since capping is a contaminant control measure for potential benthic effects, the contaminated material should be placed so that the exposure of the material prior to capping is minimized. In most cases, the water-column dispersion and bottom spread occurring during placement should also be reduced to the greatest possible extent. This minimizes the release of contaminants during placement and provides for easier capping. If the placement of the contaminated sediment has potentially unacceptable water-column impacts, controls to specifically reduce water-column dispersion, (for example submerged discharge), may be required.

For LBC, the dredging equipment and placement technique for contaminated sediment must result in a tight, compact mound which is easily capped. Compact mounds generally result when the material is dredged and placed at or near its in situ density prior to dredging. This is most easily accomplished with mechanical dredging techniques and precision point discharges from barges.

For contained CAD projects, the provision for lateral containment, in the form of a bottom depression or other features, defines and limits the extent of bottom spread. For this reason, either mechanical dredging or hydraulic placement of the contaminated material may be acceptable for CAD. If the contaminated material is placed hydraulically, a suitable time period (usually a few weeks) must be allowed for settling and consolidation to occur prior to placement of the capping material to avoid potential mixing of the materials, unless capped by slow sprinkling of sand.

Capping material placement

Placement of capping material is accomplished so that the deposit forms a layer of the required thickness over the contaminated material. For most projects, the surface area of the contaminated material to be capped may be several hundred feet or more in diameter. Placement of a cap of required thickness over such an area may require spreading the material to some degree to achieve coverage.

The equipment and placement technique are selected and the rate of application of capping material is controlled to avoid displacement or mixing with the previously placed contaminated material to the greatest extent possible. Placement of capping material at equal or lesser density than the contaminated material generally meets this requirement. However, sand caps have been successfully placed over fine-grained contaminated material. Since capping materials are not contaminated, water-column dispersion of capping material is not usually of concern (except for loss when slowly placing a sand cap), the use

of submerged discharge for capping placement need only be considered from the standpoint of placement control.

Geotechnical considerations

Geotechnical considerations are important in capping because of the fact that most contaminated sediments are fine-grained silts and clays and usually have high water contents and low shear strengths in situ. Once sediments are dredged and placed at a subaqueous site, the water contents may be higher and the shear strengths lower than in situ.

Capping involves the placement of a layer of clean sediment of perhaps 0.9 m (3 ft) or more in thickness over such low-shear-strength material. Field monitoring data have definitively shown that contaminated sediments with low strength have been successfully capped with slow placement of sandy material. The geotechnical considerations involved can be described in terms of the ability of a capped deposit with given shear strength to support a cap from the standpoint of slope stability and/or bearing capacity. (Ling et al. 1996.)

Only very limited geotechnical evaluations have been considered in past capping projects. In virtually all of past capping projects, the design was empirical, i.e., prior field experience showed that it worked, but actual geotechnical design calculations were not conducted. Research on this topic is now underway and more detailed guidance on this aspect of capping design will be provided in the future. Additional research is also planned to define geotechnical design for bearing capacity, slope failure, loading rate, impact penetration, etc.[1] For the present time, geotechnical aspects of capping project design are limited to the evaluation of compatibility of equipment and placement technique for contaminated and capping sediments with sediment properties as described in the following section.

Surface discharge using conventional equipment

The behavior of a discharge of dredged material into open water is dependent on a number of factors which include the physical characteristics of the material, the site conditions, and the method of dredging and placement (i.e., from barges, hopper dredges, or direct pipeline) (HQDOA 1983). Dredged material released at the water's surface using conventional equipment tends to descend rapidly to the bottom as a dense jet with minimal short-term losses to the overlying water column (Bokuniewicz et al. 1978; Truitt 1986a,b). Thus, the use of conventional equipment can be considered for placement of both contaminated and capping

[1] Rollings, M. (2000). "Geotechnical design guidance for contaminated aquatic disposal." *DOER Technical Notes Collection* (ERDC TN-DOER-N5). U.S. Army Engineer Research and Development Center, Vicksburg, MS. www.wes.army.mil

material if the bottom spread and watercolumn dispersion resulting from such a discharge are acceptable.

The surface release of mechanically dredged material from barges results in a faster descent, tighter mound, and less water-column dispersion as compared to surface discharge of hydraulically dredged material from a pipeline. Placement characteristics resulting from surface release of hydraulically dredged material from a hopper dredge fall between the characteristics resulting from surface release of hydraulically dredged material from barges and from surface discharge of hydraulically dredged material from a pipeline; that is, the descent is slower than the former but faster than the latter, the mound is looser than the former but tighter than the latter, and more water-column dispersion results from the former than from the latter.

Field experiences with LBC operations in Long Island Sound and the New York Bight have shown that mechanically dredged silt and clay released from barges tends to remain in clumps during descent and forms nonflowing discrete mounds on the bottom which can be effectively capped. Such mounds have been capped with both mechanically dredged material released from barges and with material released from hopper dredges (O'Connor and O'Connor 1983; Morton 1983, 1987). In fact, mechanically dredged cohesive sediments often remain in a clumped condition, reflecting the shape of the dredge bucket. Mounds of such material are very stable, resist displacement during capping operations, and present conditions ideal for subsequent LBC (Sanderson and McKnight 1986). However, these mounds may experience initial surface erosion due to irregular surface geometry and higher friction coefficients. A conceptual illustration showing the use of conventional equipment for capping is shown in Figure 19.

Spreading by barge movement

A layer of capping material can be spread or gradually built up using bottom-dump barges if provisions are made for controlled opening or movement of the barges. This can be accomplished by slowly opening a conventional split-hull barge over a period of tens of minutes, depending on the size of the barge and site conditions. Such techniques have been successfully used for controlled placement of predominantly coarse-grained, sandy capping materials at sites in Puget Sound (Sumeri 1989). The gradual opening of the split-hull or multicompartmented barges allows the material to be released slowly from the barge in a sprinkling manner. If tugs are used to slowly move the barge during the release, the material can be spread in a thin layer over a large area (Figure 20). Multiple barge loads are necessary to cap larger areas in an overlapping manner. The gradual release of mechanically dredged fine-grained silts and clays from barges may not be possible because of potential "bridging" action; that is, the cohesion of such materials may cause the entire barge load to "bridge" the split-hull opening until a critical point is reached, and the entire barge load is released. If the water content of fine-grained material is high, the material exits the barge in a matter of seconds as a dense slurry, even though the barge is only partially opened.

Spreading of thin layers of cap material over large areas can also be accomplished by gradually opening a conventional split-hull barge while underway by tow. These techniques were used for in situ capping operations at Eagle Harbor, Washington (Sumeri 1995).

Spreading by hopper dredges

Hopper dredges can also be used to spread a sand cap. During the summer and fall of 1993, the Port Newark/Elizabeth capping project in New York Bight used hopper dredges to spread a sand cap over 443,468 cu m (580,000 cu yd) of dioxin contaminated sediments. To facilitate spreading the cap in a thin layer (152 mm (6 in.)) to quickly isolate the contaminants and to lower the potential for resuspension of the contaminated material, conventional point dumping was not done. Instead, a split-hull dredge cracked the hull open 25.4 mm (12 in.) and released its load over a 20- to 30-min period while sailing at 1 to 2 knots. Also, as alternative means of placing the cap, another dredge used pump out over the side of the vessel through twin vertical pipes with end plates to force the slurry into the direction the vessel was traveling. As with the cracked-hull method described, injecting the slurry into the direction of travel of the vessel increased turbulence, reducing the downward velocity of the slurry particles and thus the potential for resuspension of the contaminated sediments. A modified version of the STFATE model was used to predict the width of coverage from a single pass and the maximum thickness produced. Randall, Clausner, and Johnson (1994) describe this work in detail.

Pipeline with baffle plate or sand box

Spreading placement for capping operations can be easily accomplished with surface discharge from a pipeline aided by an energy dissipating device such as a baffle plate or sand box attached to the end of the pipeline. Hydraulic placement is well-suited to placement of thin layers over large surface areas.

A baffle plate (Figure 21), sometimes called an impingement or momentum plate, serves two functions. First, as the pipeline discharge strikes the plate, the discharge is sprayed in a radial fashion and the discharge is allowed to fall vertically into the water column. The decrease in velocity reduces the potential of the discharge to erode material already in place. Second, the angle of the plate can be adjusted so that the momentum of the discharge exerts a force which can be used to swing the end of the floating pipeline in an arc. Such plates are commonly used in river dredging operations where material is deposited in thin layers in areas adjacent to the dredged channel (Elliot 1932). Such equipment can be used in capping operations to spread very thin layers of material over a large area, thereby gradually building up the required capping thickness.

A device called a "sand box" (Figure 22) serves a similar function. This device acts as a diffuser box with baffles and side boards to dissipate the energy of the discharge. The bottom and sides of the box are constructed as an open

grid or with a pattern of holes so that the discharge is released through the entire box. The box is mounted on the end of a spud barge so that it can be swung about the spud using anchor lines. This device was used for capping operations at the Simpson-Tacoma Kraft site in Puget Sound (Sumeri 1989).

Submerged discharge

If the placement of the contaminated sediment with surface discharge results in unacceptable water-column impacts, or if the anticipated degree of spreading and water-column dispersion for either the contaminated or capping material is unacceptable, submerged discharge is a potential control measure.

In the case of contaminated dredged material, submerged discharge serves to isolate the material from the water column during at least part of its descent. This isolation can minimize potential chemical releases because of water-column dispersion and significantly reduce entrainment of site water, thereby reducing bottom spread and the area and volume to be capped. In the case of capping material, the use of submerged discharge provides additional control and accuracy during placement, thereby potentially reducing the volume of capping material required. Several equipment alternatives are available for submerged discharge (Palermo 1994) and are described in the following paragraphs.

Submerged diffuser

A submerged diffuser (Figure 23) can be used to provide additional control for submerged pipeline discharge. The diffuser consists of conical and radial sections joined to form the diffuser assembly, which is mounted to the end of the discharge pipeline. A small discharge barge is required to position the diffuser and pipeline vertically in the water column. By positioning the diffuser several meters (feet) above the bottom, the discharge is isolated from the upper water column. The diffuser design allows material to be radially discharged parallel to the bottom and with a reduced velocity. Movement of the discharge barge can serve to spread the discharge to cap larger areas. The diffuser can also be used with any hydraulic pipeline operation including hydraulic pipeline dredges, pump out from hopper dredges, and reslurried pump out from barges.

A design for a submerged diffuser system was developed by JBF Corporation as a part of the USACE Dredged Material Research Program (DMRP) (Barnard 1978; Neal, Henry, and Greene 1978). This design consists of a funnel-shaped diffuser oriented vertically at the end of a submerged pipeline section which discharges the slurry radially. The diffuser and pipe section is attached to a pivot boom system on a discharge barge. Design specifications for this submerged diffuser system are available (Neal, Henry, and Greene 1978; Palermo in preparation).

A variation of the DMRP diffuser design was used in an equipment demonstration at Calumet Harbor, Illinois. Although not constructed to the

DMRP specifications, this diffuser significantly reduced pipeline exit velocity, confined the discharged material to the lower portion of the water column, and reduced suspended solids in the upper portion of the water column (Hayes, McLellan, and Truitt 1988). Diffusers have been constructed using the DMRP design and used at a habitat creation project in the Chesapeake Bay (Earhart, Clarke, and Shipley 1988), and at a Superfund Pilot Dredging Project at New Bedford Harbor, Massachusetts, involving subaqueous capping (USAE Division, New England 1990). At the Chesapeake Bay site, the diffuser was used to effectively achieve dredged material mounding prior to placement of a layer of oyster shell to provide substrate for attachment of oyster spat. At the New Bedford site, the diffuser was used to place contaminated sediment in an excavated subaqueous cell and was effective in reducing sediment resuspension and in controlling placement of contaminated sediment. However, capping operations were started immediately and positioning of the diffuser within 0.6 m (2 ft) of the contaminated sediment layer resulted in mixing of cap sediment with contaminated sediment. These results indicate the need for a high degree of control when capping newly placed slurry with a diffuser and the need for adequate time to allow for some self-weight consolidation of slurry material prior to capping. Diffusers have also been successfully used to place and cap contaminated sediments at projects in Rotterdam Harbor, the Netherlands (d'Angremond, de Jong, and de Waard 1984) and in Antwerp Harbor in Belgium (Van Wijck and Smits 1991).

Sand spreader barge

Specialized equipment for hydraulic spreading of sand for capping has been used by the Japanese (Kikegawa 1983, Sanderson and McKnight 1986). This equipment employs the basic features of a hydraulic dredge with submerged discharge. Material is brought to the spreader by barge, where water is added to slurry the sand. The spreader then pumps the slurried sand through a submerged pipeline. A winch and anchoring system is used to swing the spreader from side to side and forward, thereby capping a large area.

Gravity-fed downpipe (Tremie)

Tremie equipment can be used for submerged discharge of either mechanically or hydraulically dredged material. The equipment consists of a large-diameter conduit extending vertically from the surface through the water column to some point near or above the bottom. The conduit provides the desired isolation of the discharge from the upper water column and improved placement accuracy. However, because the conduit is a large-diameter straight vertical section, there is little reduction in momentum or impact energy over conventional surface discharge. The weight and rigid nature of the conduit require a sound structural design and consideration of the forces due to currents and waves.

The Japanese have used tremie technology in the design of specialized conveyor barges for capping operations (Togashi 1983, Sanderson and McKnight 1986). This equipment consists of a tremie conduit attached to a barge equipped with a conveyor (Figure 24). The material is initially placed in the barge mechanically. The conveyor then mechanically feeds the material to the tremie conduit. A telescoping feature of the tremie allows placement at depths of up to approximately 12 m (40 ft). Anchor and winch systems are used to swing the barge from side to side and forward so that larger areas can be capped, similar to the sand spreader barge. A tremie tube was considered for placement of materials for a proposed CAD site for U.S. Navy Everett Homeport project (Palermo et al. 1989).

Hopper dredge pumpdown

Some hopper dredges have pump-out capability by which material from the hoppers is discharged like a conventional hydraulic pipeline dredge. In addition, some have further modifications that allow pumps to be reversed so that material is pumped down through the dredge's extended dragarms. Because of the expansion at the draghead, the result is similar to using a diffuser section. Pump-out depth is limited, however, to the maximum dredging depth, typically about 18 to 21 m (60 to 70 ft).

Compatibility of operations

An acceptable match of equipment and placement techniques for contaminated and capping material is essential to avoid displacement of the previously placed contaminated material or excessive mixing of capping and contaminated material. The availability of certain types of equipment and the distance between dredging and payment sites may also influence selection of compatible equipment types. The nature of the materials (cohesive versus noncohesive), the dredging method (mechanical versus hydraulic), the method of discharge (instantaneous dump from hopper dredge or barge versus continuous pipeline), the location of discharge (surface or submerged), frequency and scheduling of discharges, physical characteristics of discharge material, and other factors influence the tendency of the material to mound or flow and the tendency to displace or mix with material already placed.

Navigation and positioning controls

Controlled and accurate placement of both the contaminated and capping material is crucial for a successful capping project. Once the dredging equipment and placement techniques and potential capping site have been selected, the needs for navigation and positioning equipment and controls can be addressed. The objective here is to place both the contaminated and capping materials (whether by the barge load, hopper load, or by pipeline) at the desired

location in a consistently accurate manner so that adequate coverage by the cap is attained.

For pipeline placement in shallow water, the desired positioning of the pipeline discharge can be maintained with little difficulty. Accurate navigation to the placement site and precise positioning during material placement by bottom-dump barge or hopper dredge is more difficult, especially for sites well offshore. State-of-the-art equipment (i.e., differential global positioning system (DGPS) or microwave systems) and techniques must be employed to assure accurate point placement to the extent deemed necessary. Taut-moored buoys, mooring barges, various acoustical positioning devices, and computer assisted, real-time helmsman's aids should be considered. In all cases, barges or scows must be required to release the material within a prescribed radius of the designated point of placement. A positioning system for the disposal barges must be specified which has sufficient accuracy to ensure placement within the minimum specified radius of placement. Diligent inspection of operations to ensure compliance with specifications is essential.

Sediment Dispersion and Mound Development

The physical behavior of a dredged material discharge depends on the type of dredging and disposal operation used, nature of the material (physical characteristics), and hydrodynamics of the disposal site. For capping operations, it is essential to determine beforehand the nature of the discharge for both contaminated and capping material. The degree of dispersion and associated water-column contaminant release dictates whether a given discharge is acceptable from the standpoint of water-column impacts. The geometry of the subaqueous deposit or mound dictates the required area to be capped and cap configuration.

A knowledge of the short-term physical fate of both the contaminated material and capping material is necessary to determine the acceptability of the equipment and placement operation under consideration. Short-term fate is defined as the behavior exhibited by the material during and immediately following discharge. The dispersion of material released into the water column and the deposition of the material on the bottom are also of interest. These processes occur over a time period of a few minutes to several hours for a single release from a barge or hopper dredge.

In addition to physical dispersion of suspended material, an evaluation of water-column mixing of released contaminants or suspended dredged material is necessary whenever potential water-column contaminant effects are of concern. Such an evaluation may involve comparison of predicted water-column contaminant concentrations with water quality criteria (or standards) or predicted suspended dredged material concentrations with bioassay test results. Water column effects measured in the field on actual projects (i.e., Truitt 1986a) may be valuable in quantifying water quality effects. For capping operations, such

evaluations are normally required for the contaminated material to determine if water-column control measures (i.e., submerged discharge) are necessary during placement. In addition, the prediction indicates what portion of the contaminated material is dispersed during placement and is not capped.

The physical development of a mound or deposit on the bottom due to a number of barge or hopper releases or prolonged discharge from a pipeline is also of interest. Such information can be used to define the areal extent of the mound or deposit for the contaminated material. This dictates the required volume of capping material.

Models for prediction of short-term fate during placement

A computer model is available for evaluating the short-term fate of dredged material discharges in open water from hoppers or barges. The model is called the Short Term FATE (STFATE) model (Johnson et al. 1993; Johnson and Fong 1993) and can be run on a personal computer (PC). These models are available as a part of the Automated Dredging and Disposal Alternatives Management System (ADDAMS) (Schroeder and Palermo 1990). Versions of these models are also included in the Ocean and Inland testing manuals (USACE/EPA 1991 and in preparation).

Input data required to run the models include: (a) description of the disposal operation, (b) description of the disposal site, (c) description of the dredged material, (d) model coefficients, (e) controls for input, execution, and output. More detailed descriptions and guidance for selection of values for many of the parameters is provided directly on-line in the system software or default values may be used.

Model output includes a time-history of the descent and collapse phases of the discharge and suspended sediment concentrations for various particle size ranges as a function of depth and time. At the conclusion of the model simulation, the thickness of the deposited material on the bottom is given. This allows an estimate of the areal extent or "footprint" of contaminated material as deposited on the bottom for a single disposal operation (i.e., a single barge or hopper load of material).

Evaluation of spread and mounding

The mound geometry, including contaminated material mound and cap, will influence the design of the cap and volume of capping material required. The smaller the footprint of the contaminated material as placed, the less volume of capping material will be required to achieve a given cap thickness.

For LBC sites, the geometry of the contaminated material mound depends on the physical characteristics of the material (grain size and cohesion) and the placement technique used (hydraulic placement will result in greater spread than

mechanical placement). Assuming that the material from multiple barge loads or pipeline can be accurately placed at a single point, the angle of repose taken by the material and the total volume placed will dictate the mound spread.

However, few data are available on the volume changes resulting from entrainment of water during open water placement or the shear strengths of dredged material initially deposited in open water sites. For these reasons, a priori estimates of mound spread made to date have been made based on the observed characteristics of previous mounds created with similar placement techniques and similar sediments (Palermo et al. 1989). Models have been developed which will account for the development of mounds as the result of a number of barge or hopper discharges (Moritz and Randall 1995; SAIC 1995a,b).

The Corps' mound building model which models Multiple Disposals from barges and hopper dredges and their FATE (MDFATE), is a modification of the STFATE model. In the MDFATE model, a streamlined version of the STFATE model is run for each barge disposal. Thus, the input requirements for MDFATE are similar to those for STFATE. In MDFATE, the program keeps track of the mound thickness in each grid cell, then algebraically adds the thickness from subsequent disposals. MDFATE allows a number of typical disposal patterns to be automated, it allows moving barges and can import actual site bathymetry in real world coordinates. MDFATE also allows interaction with the Long Term FATE of Dredged Material (LTFATE) model (Scheffner, Thevenot, Tallent, and Mason 1995). This allows the mound created in MDFATE to be eroded by waves and currents during mound creations that may last for months. Similar to the output from STFATE, output from the MDFATE model includes the volume of material on the bottom and contour and cross section plots of mound bathymetry. MDFATE has been verified on several projects (Moritz 1997), including hindcasting the 1993 capping project at the New York Mud Dump ocean site.

The DAMOS capping model (Wiley 1995) is also based on the STFATE model. While it does not consider moving vessels or erosion by waves and currents, it has the advantage of having been verified for a number of mounds constructed by the New England Division in Long Island Sound.

Typical contaminated mound geometry

As noted previously, for LBC projects, virtually all of the mounds created have been constructed using mechanical dredging with transportation and placement by bottom-dump barges. The resulting mounds created have had reasonably consistent geometries. Most mounds have been round or elliptical in shape, with a defined crest that is relatively flat, a main mound side slope (also termed the inner flank), sometimes an outer flank, and a thin outer apron. The dimensions for the side slopes and apron widths are based on those seen at the Port Newark/Elizabeth mound created in the Mud Dump site in 1993. The following paragraphs describe each of the mound features in more detail.

Mound crest

Most contaminated mounds to date have had main mound crest elevations of 1 to 2 m, though some contaminated mounds with elevations of 3+ m have been constructed. Higher mounds have been constructed from noncontaminated material. For point-dumped projects in Long Island Sound, mound crests have generally been about circles or ellipses 100 to 200 m in diameter, reflecting good control of the disposal process around a taut-moored buoy (disposal within about 25 m of the buoy) for moderate sized projects, generally 15,292 to 76,460 cu m (20,000 to 100,000 cy yd). The 1993 Port Newark Elizabeth project used disposal lanes, 150 m in width and 300 to 420 m long, to create a triangular shaped mound, approximately 630 by 645 m, with peak elevations of 1.5 to 2.4 m.

Inner flank

At the edge of the main mound, the inner flank of the mounds slope downward at a slope of approximately 1:35 to 1:70 with most of the mound slopes between 1:40 and 1:50. For the Port Newark/Elizabeth mound, the inner flank extended from the mound crest down to an elevation of about 1.0 m above the preplacement bottom.

Outer flank

For the Port Newark project, a break in slope generally occurred at the 1.0-m el, the outerflank then sloped down to an elevation of about 0.3 m at a slope of about 1:115. Data from New England Division projects have not been examined in sufficient detail to determine if a similar feature exists for those mounds.

Apron

During the dynamic collapse phase (when the energy of the vertically descending jet of material disposed from a barge or hopper dredge is converted to horizontal velocity), some portion of the low shear strength, fine-grained material with high water contents may be transported a considerable distance from the disposal point. At the completion of the contaminated material placement, an apron of fine-grained material, typically 1 to 15 cm in thickness but extending up to several hundreds of meters beyond the main mound flanks has occurred on almost all LBC projects. Defining the apron as the material less than 15 cm is done because 15 to 20 cm is the resolution limit for high-quality bathymetry in water depths of 25 m or less. A sediment profiling camera (SPC) can reliably measure apron thickness from 1 to 2 cm up to 20 cm. Thus, the outer limit of the apron should be defined as the point at which the apron can no longer be conclusively distinguished by the SPC, a thickness of 1 to 2 cm. Some contaminated material extends beyond the apron edge as defined by the 1 to

2 cm SPC limit, however the percentage of the total volume is likely extremely small.

The apron typically exhibits an overall slope of 1v:1000+h at the Port Newark/Elizabeth project, and overall apron slope of about 1:2,000 was observed on downward sloping bottoms. If the inner edge of the apron is assumed to be 15 cm in thickness, the width of the apron for the Port Newark Elizabeth project was about 300 m.

The STFATE and MDFATE models and the DAMOS capping model can be used to predict the apron dimensions.

Recent experience in 1997 with a USAED, New York, capping project placed in the Mud Dump site illustrated the potential for slope adjustments when fine-grained mounds are created with heights exceeding about 3 m (10 ft). In one case, a portion of a contaminated mound with a height of 3.7 m (12 ft) had a slope adjustment resulting in an after adjustment height of 1.8 to 2.4 m (6 to 8 ft) and a movement of material outward of about 305 m (1,000 ft). This section of mound was placed on an ambient slope of up to 0.025 rad (1.45 deg) which likely contributed to the adjustment and the outward movement. In a second case, a portion of the same mound with an elevation exceeding 3 m (10 ft) experienced an apparent slope adjustment after capping began. Losses in elevation of 0.9 to 1.2 m (3 to 4 ft) occurred as a result of the adjustment, though the significant outward movement seen on the upcapped section did not occur. This section of the mound was placed on a nearly flat slope. The above illustrates the need to consider the potential for slope adjustments in mounds over 1.8 to 2.4 m (6 to 8 ft) tall. Analysis of slope stability for taller mounds, particularly those placed on slopes, is recommended.

Exposure time prior to capping

Scheduling of the contaminated material placement and capping operation must satisfy environmental and engineering/operational constraints. Following the placement of contaminated material, there is necessarily some time lag prior to completion of the capping operation. This results in some exposure time for benthic organisms to colonize a portion of the contaminated material deposit. Placement of the cap material must begin as soon as practicable following completion of the placement of contaminated material to minimize this exposure time. However, a delay of 1 to 2 weeks is desirable from an engineering standpoint to allow initial consolidation of the contaminated material to occur, with an accompanying increase in shear strength, prior to placement of the cap.

Factors to consider in arriving at an appropriate exposure time are:

a. Potential effects resulting from exposure prior to capping.

b. Estimates of time required for initial colonization of the site by benthic organisms.

c. Estimates of time required for initial consolidation of the contaminated material because of self-weight.

d. Monitoring requirements prior to cap placement.

The process of recolonization by opportunistic species may begin almost as soon as contaminated material placement operations are completed (Rhoads and Boyer 1982, Rhoads and Germano 1982). However, probably several weeks must pass before any significant recolonization by organisms occurs (Scott et al. 1987). Bioaccumulation by opportunistic species can occur during this time, but the species will be buried and thus physically isolated by placement of the cap. It is therefore unlikely that any significant bioaccumulation will result in unacceptable effects during this period of time.

Some delay between completion of contaminated material placement and initiation of capping is desirable from an engineering standpoint. Consolidation of the contaminated material and a corresponding increase in density and strength occurs due to the weight of the material as it is placed in the deposit. This process is called self-weight consolidation. The contaminated material should be allowed to undergo initial self-weight consolidation prior to capping to increase its stability and resistance to displacement during cap placement. This is especially important for slurried materials placed by pipeline or by hopper dredge. For slurried materials, a large portion of the self-weight consolidation occurs within a few weeks of placement. Mechanically dredged materials placed by barge release are initially deposited at essentially the same density at which they were dredged, and the potential degree of self-weight consolidation is less than for slurried materials.

Monitoring is required to determine the areal extent of the contaminated deposit prior to capping. Surveys and other sampling and monitoring activities may require several weeks to complete. An appropriate delay between contaminated material placement and capping must balance environmental exposure with the engineering requirements of stability and scheduling constraints for monitoring and dredging required for capping. Considering the times required for recolonization and consolidation, a time lag of 3 to 4 weeks between completion of contaminated material placement and initiation of capping is generally considered acceptable.

Cap Design

The composition and dimensions (thickness) of the components of a cap can be referred to as the cap design. This design must physically isolate the contaminated sediments from the benthic environment and control potential flux of contaminants through the cap. The design must also be compatible with available equipment and placement techniques.

The composition of caps for dredged material projects are typically a single layer of clean sediments because: relatively large volumes of cap material are

involved; clean sediments from other dredging projects are often available as cap materials; and, dredged material capping sites with low potential for erosion can be selected. The discussion of dredged material cap design herein therefore focuses on the thickness of the cap as the major design criterion.

Required cap thickness

Determining the minimum required cap thickness depends on the physical and chemical properties of the contaminated and capping sediments, hydrodynamic conditions such as currents and waves, potential for bioturbation of the cap by aquatic organisms, potential for consolidation of the cap and underlying sediments, and operational considerations. Total thickness can be composed of components for bioturbation, consolidation, erosion, operational considerations, and chemical isolation. Schematics of the cap thickness components and potential physical changes of the cap thickness due to erosion, consolidation, etc. are shown in Figure 25.

The thickness for chemical isolation (if required) and/or the thickness for bioturbation must be maintained to ensure long-term integrity of the cap. The integrity of the cap from the standpoint of physical changes in cap thickness and potential for a physical reduction in cap thickness resulting from the effects of consolidation and erosion can be evaluated once the overall size and configuration of the capped mound or deposit and resulting water depth over the cap is determined. The design cap thickness for the various components can then be adjusted by iterative calculations, if needed.

At present, the design of caps composed of clean sediments is based on a combination of laboratory tests and models of the various processes involved (contaminant flux, bioturbation, consolidation, and erosion), field experience, and monitoring data. Since the number of carefully designed, constructed, and monitored capping projects is limited, the design approach is presently based on the conservative premise that the cap thickness components are additive. No dual function performed by cap components is considered. As more data become available on the interaction of the processes affecting cap effectiveness, this additive design approach can be refined.

The recommended sequence for determining the design cap thickness is :

a.. Assess the bioturbation potential of indigenous benthos and determine an appropriate cap thickness component for bioturbation.

b. Determine if the capping material is compressible, and if so, evaluate potential consolidation of the cap material after placement. If contaminated sediments or native underlying sediments are compressible, evaluate potential consolidation of those materials.

c. Considering the mound or deposit geometry, and site conditions, conduct a screening evaluation of potential erosion. If there is potential for

erosion, conduct a detailed evaluation, considering both ambient currents and episodic events such as storms. If required, add a thickness component to offset potential erosion.

d. Evaluate operational considerations and determine restrictions or additional protective measures (e.g., institutional controls) needed to assure cap integrity.

e. If a design function of the cap is to control contaminant flux, evaluate the potential for short-term and long-term flux of contaminants through the cap as necessary. Determine any necessary additional cap thickness component for chemical isolation based on modeling and/or testing.

Bioturbation

A design objective of a dredged material cap is to physically isolate the contaminated material from benthic organisms. In the context of capping, bioturbation may be defined as the disturbance and mixing of sediments by benthic organisms. The importance of bioturbation by burrowing aquatic organisms to the mobility of contaminants cannot be overestimated . In addition to the disruption (breaching) of a thin cap that can result when organisms actively rework the surface sediments, there is the problem of direct exposure of infaunal organisms to the underlying contaminated sediment. The best available knowledge on local infauna must supplement generic assumptions concerning the bioturbation process.

Aquatic organisms that live on or in bottom sediments can greatly increase the movement of contaminants (solid and dissolved) through the direct movement of sediment particles or irrigation of porewater, increasing the surface area of sediments exposed to the water column, and as a food for epibenthic or pelagic organisms grazing on the benthos. The specific assemblage of benthic species which recolonizes the site, the bioturbation depth profile, and the abundances of dominant organisms are key factors in determining the degree to which bioturbation will influence cap performance.

The depth to which organisms will bioturbate is dependent on behaviors of specific organisms and the characteristics of the substrate (i.e., grain size, compaction, organic content, porewater geochemistry, etc.). In general, the depth of recolonization by marine benthos is greater than that of freshwater benthos. Recolonization by benthic infauna at marine dredged material caps is primarily by suspension feeders as opposed to burrowing organisms (Morton, 1989; Myers 1979).

The intensity of bioturbation is greatest at the sediment surface and generally decreases with depth. Three zones of bioturbation are of importance (Figure 26). A surficial layer thickness of sediment will be effectively overturned by shallow bioturbating organisms and can be assumed to be a continually and completely mixed sediment layer for purposes of cap design. This layer is generally a few

centimeters in thickness. Depending on the site characteristics, a number of middepth burrowing organisms recolonize the site over periods of time. The level of bioturbating activity for these organisms will decrease with depth as shown in Figure 26. The species and associated behaviors of organisms which occupy these surface and middepth zones are generally well known on a regional basis. There may also be potential for colonization by deep burrowing organisms (such as certain species of mud shrimp) which may borrow to depths of 1 m or more. However, knowledge of these organisms is very limited. These cap design criteria assume that deep bioturbators are not present in significant numbers.

Cap thickness required for bioturbation, T_b, should be determined based on the known behavior and depth distribution of infaunal organisms likely to colonize the site in significant numbers. Bioturbation depths are highly variable, but have been on the order of 30 to 60 cm (1 to 2 ft) for most infaunal organisms which populate a site in great numbers. Consulting with experts on bioturbation in the region of the disposal site location is desirable. The thickness needed to prevent breaching of cap integrity through bioturbation can be determined indirectly from other information sources. For example, the benthic biota of U.S. coastal and freshwater areas have been fairly well examined, and estimates of the depth to which benthic animals burrow should be available from regional authorities (Rhoads and Carey 1997).

Consolidation

Consolidation of the cap, contaminated material, or underlying native sediments may occur over a period of time following cap placement but does not occur repeatedly. If a fine-grained cap material will be used, consolidation of the cap may require an added cap thickness component in the design so that the consolidated cap will remain at the required thickness. If any of the sediments (cap, contaminated, or native sediment) are compressible, a prediction of consolidation is important in interpreting monitoring data to differentiate between changes in surface elevation because of consolidation, as opposed to those potentially as a result of erosion. It is important to note that the total mound height for an LBC project or fill height for a CAD project can decrease (resulting from consolidation of the contaminated layer or underlying native sediment) without the need to nourish the cap.

The consolidation analysis also holds importance for any required assessment of potential long-term flux of contaminants through the cap. The magnitude of consolidation of underlying sediments will determine the amount of water potentially moving (advecting) upward into the cap. Changes in the void ratio of the cap must also be considered in determining the distance to which this water is expressed upward into the cap.

If the selected material for the cap is fine-grained material (defined as material with more than 50 percent by weight passing a no. 200 sieve), the change in thickness of the material because of its own self-weight or other cap components should be considered in the overall design of the cap thickness. An

evaluation of cap consolidation should be made in this case, and an additional cap thickness component for consolidation, T_c, should be added so that the appropriate cap thickness is maintained. Such consolidation occurs over a period of time following cap placement but does not occur more than once.

If the cap material is not a fine-grained material, no consolidation of the cap may be assumed, and no additional increase in the isolation thickness is necessary. However, consolidation of the underlying contaminated sediments may occur, and a consolidation analysis may be necessary to properly interpret monitoring data.

Erosion

If there is potential for erosion, the total cap thickness should include a thickness component for erosion, T_e, which may occur primarily because of long-term continuous processes (i.e., tidal currents and normal wave activity) or episodic events such as storms. This portion of the total thickness can be lost after many years of normal levels of wave and current activity, after a abnormally severe storm season, or in a few days during extreme events. Monitoring activities should result in detecting the loss of cap followed by a management decision to place additional material to bring the cap back to its design thickness.

A screening level assessment of erosion potential should first be conducted. This assessment may be conducted as a part of the site screening process. This assessment can be based on simple analytical or empirical methods. If the screening assessment indicates little or no potential for erosion, no detailed assessment need be conducted, and no erosion cap thickness component is needed. If the screening assessment indicates a potential for erosion, a more detailed assessment should be conducted. If the contaminated material is to be hydraulically placed (as for a CAD site) or a site with higher energy potential is being considered, a thorough analysis of the potential for resuspension and erosion must be performed, to include frequency considerations.

Based on the detailed assessment, a value of T_e should be added as the erosion cap thickness component. The criteria used to calculate the thickness to be added is equivalent to that used for the site screening. For projects in which no subsequent capping is anticipated for a long time period (several decades or longer) or for which materials for cap nourishment are not easily obtained, the recommended cap thickness component to be added, T_e, should be equivalent to the calculated net cap erosion over the major portion of the mound over a period of 20 years of normal current/wave energies or for a 100-year extreme event. The 20-year ambient time interval, and 100-year return interval for storms is based on field experience gained to date. Time periods of 20 and 100 years are in the range of design periods for many engineering structures. Note that calculated erosion at localized portions of the mound or feature may be somewhat greater than the value of T_e selected. The corners of a mound would normally have an overlap of capping material and the crest of a mound would

normally have a greater cap thickness, therefore somewhat larger erosion could be tolerated over these portions of a mound.

Selection of other values of ambient time periods, return intervals, etc. for calculating erosion thickness should be based on site-specific factors (e.g., the degree of contamination, distance to other resources, etc.), the level of confidence in the calculations, and the acceptable level of risk. For projects in which subsequent capping is planned or for which materials for cap nourishment can be easily obtained, higher erosion rates may be considered. In areas where available capping materials and current and wave conditions are severe, a coarse-grained layer of material may be incorporated into the cap design to provide protection against erosive currents at the site.

Selecting a cap thickness component for erosion is a function of the acceptable level of risk. Definitive guidance is difficult because the level of risk acceptable will likely vary from project to project.

Operational concerns

At some locations, other considerations, termed operational, may have to be considered when determining the final cap thickness. These include anchoring, ability to place thin layers, unevenness of material placement, etc. If these are serious considerations, then locations that have significant potential for these types of operational considerations would be poor choices for capping projects.

Vessel anchors have the potential to disturb bottom sediments (as do trawlers). While most any location in shallow water (say 30 m or less) is subject to potential anchoring, anchoring to such a degree that cap integrity is impacted will be extremely rare. For most locations where open water dredged material placement sites are located, the anchors used by recreational vessels typically only penetrate the bottom 30 to 60 cm (1 to 2 ft). The relative area impacted by anchors compared to the size of a cap is very small. Also, when the anchors are removed, the area disturbed by the anchor is quickly filled back in. This is not true for anchors from large ships which can penetrate up to 1.5 to 3 m (5 to 10 ft). Thus an area where ships routinely anchor would be a very poor choice for a capping project.

Another operational concern is the ability to place a relatively thin cap layer. Until recently, open ocean capping operations made it very difficult to place small thicknesses (less than 30 cm). For many of those projects, the minimum cap thickness for most projects has been on the order of 75 to 120 cm (2.5 to 4 ft). Recent experience from the Port Newark/Elizabeth project at the Mud Dump (Randall, Clausner, and Johnson 1994) and Puget Sound capping projects (Nelson, Vanderheiden, and Schuldt 1994; Sumeri 1995) has shown that the sprinkling techniques developed were successful and that layers about 15 to 20 cm (0.5 to 0.75 ft) thick can be placed with reasonable assurance (though at increased cost due to increased operational controls).

The placement process will likely result in some unevenness of the cap thickness. This unevenness should be considered in calculation of the volume of capping material required.

If any of the these factors are significant for the site under consideration, an additional cap thickness component for operational concerns, T_o, should be added to the design cap thickness.

Chemical Isolation

If a design function of the cap is to control contaminant flux, the potential for short-term and long-term flux through the cap should be evaluated. The need for such an evaluation is dependent on the types of contaminants, the potential for contaminant impacts, site and operational conditions, and other factors. For example, if the reason for capping is to isolate a sediment which is nontoxic to benthic organisms and exhibits bioaccumulation only marginally above that for a reference sediment, the isolation provided by the bioturbation thickness component will likely provide sufficient control, and there is little reason to conduct a detailed assessment. Conversely, if the sediment to be capped has exhibited toxicity to benthic organisms, a detailed assessment of long-term effectiveness would be advisable.

The additional cap thickness component for chemical isolation should be determined based on modeling and/or testing as described in this section. The basis of design of a contaminant flux thickness component will be project specific. The flux rates (mass of contaminant per unit area per unit time), pore-water concentrations in the cap, and long-term accumulation of contaminants in cap sediments may be evaluated and used in the design. For example, flux and the resulting impact on overlying water quality may be compared to a water quality standard or criteria in much the same way as water-column contaminant releases during the placement process. Compliance of the flux concentrations at the boundary of the site or edge of an established mixing zone would be appropriate. In this way, the cap thickness component for isolation required to meet the water quality standards can be determined.

Chemical flux processes

Properly placed capping material acts as a filter layer against any migration of contaminated sediment particulates. There is essentially no driving force which would cause any long-term migration of sediment particles upward into a cap layer. Most contaminants of concern also tend to remain tightly bound to sediment particles. However, the potential movement of contaminants by advection (movement of pore water) upward into the cap or by molecular diffusion over extremely long periods of time is possible.

Advection refers to the movement of pore water. Such movement could occur as an essentially continuous process if there is an upward groundwater

gradient acting below the capped deposit. Tidal pumping may also cause long-term advective movement upward into a cap. Advection could also occur as a result of compression or consolidation of the contaminated sediment layer or other layers of underlying sediment.

Movement of pore water resulting from consolidation would be a finite, short-term phenomena in that the consolidation process slows as time progresses and the magnitude of consolidation is a function of the loading placed on the compressible layer. The weight of the cap will "squeeze" the sediments, and as the pore water from the sediments moves upward, it displaces pore water in the cap. The result is that contaminants can move part or all the way through the cap in a short period of time. This advective movement can cause a short-term loss, or it can reduce the breakthrough time for long-term advective/diffusive loss.

Diffusion is a molecular process in which chemical movement occurs from material with higher chemical concentration to material with lower concentration. Diffusion results in extremely slow but steady movement of contaminants. The effect of long-term diffusion on the design cap thickness is normally negligible, because long-term diffusion of contaminants through a cap is an extremely slow process, and contaminants are likely to adsorb to the clean cap material particles.

Properly designed caps act as both a filter and buffer during advection and diffusion. As pore waters move up into the relatively uncontaminated cap, the cap sediments can be expected to scavenge contaminants so that any pore water that traveled completely through the cap theoretically would carry a relatively small contaminant load to the water column. Furthermore, through-cap transport as a result of consolidation can be minimized by using a cap that has sufficient thickness to contain the entire volume of pore water that leaves the contaminated deposit during consolidation. For example, Bokuniewicz (1989) has estimated that the pore water front emanating from a consolidating 2-m-thick mud layer would only advance 24 cm into an overlying sand cap (Sumeri et al. 1991).

Contaminant flux processes are very much dependent upon the nature of the cap materials. For example, a cap composed of pure sand would not be as effective in containing contaminants as a naturally occurring sand with an associated fraction of fines and organic content.

Some components for cap thickness should not be considered in evaluating long-term flux. For example, the depth of overturning due to bioturbation can be assumed a totally mixed layer and will offer no resistance to long-term flux. The component for erosion may be assumed to be absent for short periods of time (assuming the eroded layer would be replenished). Components for operational considerations, such as an added thickness to ensure uniform placement would provide long-term resistance to flux. The void ratio or density of the cap layer after consolidation should be used in the flux assessment.

Any detailed assessment of flux must be based on modeling since the processes involved are potentially very long-term. Laboratory testing to more precisely determine parameters for the available models may also be conducted.

Modeling applications for cap effectiveness

A model has been developed by EPA to predict long-term movement of contaminants into or through caps due to advection and diffusion processes. This model has been developed based on accepted scientific principles and observed diffusion behavior in laboratory studies (Bosworth and Thibodeaux 1990; Thoma et al. 1993; Myers et al. 1996). The model considers both diffusive and advective fluxes, the thickness of sediment layers, physical properties of the sediments, concentrations of contaminants in the sediments, and other parameters.

The results generated by the model include flux rates, breakthrough times, and pore water concentrations at breakthrough. Such results can be compared to applicable water quality criteria, or interpreted in terms of a mass loss of contaminants as a function of time which could be compared to similar calculations for other remediation alternatives. The model is applicable to the case of a single-contaminated material layer and a single-cap material layer, each with a homogenous distribution of material properties. The diffusion relationships used in the model have been verified against laboratory data. However, no field verification studies for the model have been conducted.

There is a need for a comprehensive and field verified predictive tool for capping effectiveness and additional research on this topic is planned. The USACE has applied a refined version of an existing sediment flux model (Boyer et al. 1994) for capping evaluations, and more refinements to the model are planned to account for a comprehensive treatment of all pertinent processes. But in absence of such a tool, analytical models should be used in calculating long-term contaminant loss for capped deposits as long as conservative assumptions are used in the calculations.

Laboratory tests for flux evaluation

Several testing approaches have been applied to define cap thicknesses and the sediment parameters necessary to model their effectiveness in chemical isolation. Laboratory tests may be used to define sediment specific and capping material specific values of diffusion coefficients and partitioning coefficients. But, no standardized laboratory test or procedure has yet been developed to fully account for advective and diffusive processes and their interaction.

The USACE developed a first-generation capping effectiveness test in the mid-1980s as part of the initial examination of capping as a dredged material disposal alternative. The test was developed based on the work of Brannon et al. (1985, 1986), Gunnison et al. (1986), and Palermo et al. (1989). Louisiana State

University has conducted laboratory tests to assess diffusion rates for specific contaminated sediments to be capped and materials proposed for caps (Wang, Thibodeaux, Valsaraj, and Reible 1991). Diffusion coefficients for long-term modeling of diffusive transport of contaminants from contaminated sediment into cap material have also been measured using diffusion tubes (DiToro, Jeris, and Clarcia 1985). Environment Canada has performed tank tests on sediments to investigate the interaction of capping sand and compressible sediments, and additional tests are planned in which migration of contaminants due to consolidation-induced advective flow will be evaluated (Zeman 1993). The USACE has also developed leach tests to assess the quality of water moving through a contaminated sediment layer into groundwater in a confined disposal facility environment (Myers and Brannon 1991). This test is being applied to similarly assess the quality of water potentially moving upward into a cap due to advective forces.

Results of laboratory tests conducted with samples of the contaminated sediments to be capped and the proposed capping sediments should yield sediment and capping material specific values of diffusion coefficients, partitioning coefficients, and other parameters needed to model long-term cap effectiveness. Model predictions of long-term effectiveness using the laboratory derived parameters should be more reliable than predictions based on so-called default parameters.

Acceptability of flux component design

If the flux evaluation indicates that design objectives are not met, additional cap thickness can be added or cap materials with differing properties (grain size and total organic carbon (TOC)) can be considered to further decrease the contaminant flux. The evaluation process could then be run in an iterative fashion if necessary to determine the chemical isolation component needed to meet the design objectives. Of course, if no reasonable combination of cap thickness and cap material properties can meet the objectives, other alternatives or control measures must be considered.

Considerations for intermediate caps

Some capping projects could be designed in the context of anticipated multiuse or multiuser applications. In such a case, one site (e.g., a subaqueous borrow pit) could be selected for placement of contaminated sediments from several projects. If several placements of contaminated sediments are to be placed with such frequency that the site could not effectively recolonize, there would be no pathway for bioaccumulation or benthic toxicity. Also, if the site is located in a sheltered area or if the energy from low-frequency events would not cause significant erosion, no placement of cap material or placement of a intermediate cap with a lesser thickness (one that has a shorter return-period level of erosion protection or less capabilities for chemical or biological isolation) than the full design cap could be considered. Determining an

appropriate thickness for an intermediate cap would require an evaluation of the same processes as described above, but the design parameters (especially those for long-term flux, return periods for storms, etc.) should be selected to represent the time periods anticipated between dredged material and intermediate cap placement and final cap placement.

Long-Term Stability

When contaminated material is isolated from the environment through a dredged material capping operation, it is essential that the precision and thoroughness of initial cap placement be considered. The long-term integrity, or stability, of the capped deposit must also be evaluated on a regular basis. The critical element in successful performance of a cap is preservation of an adequate thickness of this clean material to prevent escape of contaminants from or intrusion of biological organisms into the contaminated sediment. In evaluating long-term cap performance, factors that must be addressed include:

a. Potential for erosion (considering the wave and current conditions at the disposal site and dredged material particle size and cohesion).

b. Possible consolidation (of capping material, contaminated sediment, and foundation material) for effect on long-term site capacity, differentiation from erosion, and quantification of contaminated pore- water volume expelled.

c. Migration of chemical contaminants (out of the contaminated sediment, through the cap, and/or into underlying foundation sediments).

Each of these factors is important and must be evaluated. However, assessment of consolidation and chemical migration are mathematically tractable, while the very stochastic nature of erosion makes it much more complicated to predict.

If any one of these factors (erosion, consolidation, and chemical migration) causes the cap to be too thin to effectively isolate the contaminated material from the surrounding environment, then remedial actions will be required to reestablish cap integrity. These issues are discussed in the following paragraphs, along with recommended techniques and computer models available for analysis.

Evaluation of consolidation

The process of consolidation occurs as soil particles are pressed together under load. Consolidation may occur in the capping material, in the contaminated sediment, and/or in the native (foundation) sediments. In the capping material, consolidation will result from self-weight of the material, while in the contaminated sediment, consolidation will occur: first from self-weight, and second as the result of the load imposed on it by the capping

material. Consolidation of the natural bottom underlying the recently constructed capped mound or deposit will occur as the result of surcharge loading caused by the mound. Consolidation will generally occur in most fine-grained soils, although the amount can vary greatly depending on a number of factors that include the particle type (clay versus silt, high versus low plasticity), moisture content/density, and permeability of the deposit, combined with the loading conditions and thickness of the compressible layers. All of the above factors interact to significantly affect the compressibility of sediment layers. Coarse-grained sediments will not consolidate appreciably.

Evaluation of erosion potential

If practical, capping should normally be conducted in predominantly nondispersive sites with relatively little potential for erosion. However, existing sites with potential for erosion can be used for capping projects. Over periods of time, studies should be conducted concerning the frequency of erosion of a specific capping material (considering grain size and cohesion) for expected and predicted wave and current conditions (to include storms) in the area. The results from such a study will provide data that can be used to predict the expected cumulative amount of erosion over time along with confidence intervals on the answers. These numbers can then be used to define the design cap thickness for erosion protection required for a given length of time (say 20 to 100 years). Obviously, periodic monitoring is required to measure existing cap thickness, along with determining requirements for reduced cap thickness contingency plans for placement of additional material.

The deposit of contaminated dredged material must also be stable against excessive erosion and resuspension of material before placement of the cap. The potential for resuspension and erosion depends on bottom current velocity, potential for wave-induced currents, sediment particle size, and sediment cohesion. Site selection criteria as described above would normally result in a site with low bottom-current velocity and little potential for erosion during the window for placement of the contaminated sediments and cap. However, if the contaminated sediment is hydraulically dredged and placed fine-grained material, a thorough analysis of the potential for resuspension and erosion must be performed.

Conventional methods for analysis of sediment transport are available to evaluate erosion potential (Teeter 1988; Dortch et al. 1990; Resio and Hands 1994; Scheffner 1991a and b). These methods can range from simple analytical techniques to numerical modeling. In the analysis of erosion, the effects of self-armoring as a result of the winnowing away of finer particles should be considered. If erosion is considered to be a problem, armoring and geotextiles may be considered as engineering approaches to overcome or protect against this problem.

The first level of investigation of cap stability against erosion involves examination of the normal wave and current regime to determine if these cause

measurable amounts of erosion. However, sites where day-to-day waves and currents cause measurable amounts of erosion would be very poor sites for capping projects. As reported by Dortch et al. (1990), based on a study by Trawle and Johnson (1986) of the Alcatraz (San Francisco Bay) aquatic disposal site, tidal currents of about 90 cm/sec were required for sand movement to begin. For significant movement of unconsolidated fine-grained material, tidal velocities of 30 cm/sec were required, while current velocities in excess of 150 cm/sec were required to cause perceptible movement of consolidated materials. It should be noted that Alcatraz does experience some level of wave activity. The values reported above do not take into account the increased erosion associated with wave activity.

Monitoring

Need for monitoring

Monitoring of capped disposal projects is required to ensure that capping acts as an effective control measure (Palermo, Fredette, and Randall 1992). Monitoring is therefore required before, during, and following placement of the contaminated and capping material to ensure that an effective cap has been constructed. (This effort also may be defined as construction monitoring.) Monitoring may also be required to ensure that the cap as constructed will be effective in isolating the contaminants and that long-term integrity of the cap is maintained. This activity also may be defined as long-term monitoring.

The monitoring discussed here does not focus on water-column processes or the water-column contaminant pathway during the placement of contaminated material prior to capping. If a determination is made that the contaminated material has potential for unacceptable water-column impacts during placement, other control measures to offset those impacts (i.e., silt curtain, diffuser, tremie pipe, etc.) and additional monitoring of water-column processes are necessary. Also, the monitoring discussed here does not focus on those aspects of open water site monitoring pertaining to site designation or on the direct physical effects of disposal. Any such monitoring would be considered in the context of the overall site selection process and site monitoring plan (Palermo 1991b).

Appropriate objectives for a capping monitoring program/plan may include the following:

a. Determine bathymetry, organisms, and sediment type at capping site.

b. Determine currents for evaluating erosion and dispersion potential.

c. Define areal extent and thickness of contaminated material deposit (to include the apron thickness) to guide cap placement.

d. Define areal extent and thickness of the cap.

e. Determine that desired capping thickness is maintained.

f. Determine cap effectiveness in isolating contaminated material from benthic environment.

g. Determine extent of recolonization of biology and bioturbation potential.

Designating management actions

When any acceptable threshold values are exceeded, some type(s) of management action(s) are required. The appropriate management actions should be determined/defined early in the disposal planning process; they should not be determined after the threshold value(s) have been exceeded.

Management options in early tiers could include increasing the level of monitoring to the next tier, the addition of more sediment to form a thicker cap, or stopping use of the site. Management options in later tiers could include stopping use of the site, changing the cap material, or the addition of a less porous material in cases where contaminant transport due to biological or physical processes is occurring. For caps that are experiencing erosion, additional cap can also be added, although it may be advisable to choose a coarser material (coarse sand or gravel) to provide armoring. In cases where extreme problems are encountered, removal of the contaminated material and placement at another site could be considered.

Conceptual Design for Capping and CAD: Overview

This section describes the conceptual design of contaminated sediment placement in Level Bottom Capping (LBC) and Contained Aquatic Disposal (CAD) facilities. Because these two types of facilities are similar in many respects, the designs will be described together in this section. Also, because of the nature of capping and CAD, several options for volumes and geometries are presented in the conceptual designs.

Though LBC and CAD are similar, the differences in construction methods highlight the advantages and disadvantages of each type of facility. LBC would require placement of the contaminated material in a mounded configuration, followed by placement of clean material to cover the mound and form a larger capped mound. A series of mounds would meet the long-term MUDS volume requirement, as shown in Figure 27. The capping material would be obtained from other dredging projects in the region (PSDDA acceptable materials). CAD would require the initial excavation of a single large pit or a series of smaller pits, with the excavated material disposed of as clean material at a PSSDA site, and, in some design options, a portion of excavated material used as capping

material for the previously used CAD cell. The layout of a series of CAD pits for the conceptual design is shown in Figure 28.

An advantage of LBC over CAD is that the time and expense of constructing the CAD pit is not required, though an existing depression can provide CAD benefits without the construction cost. However, the construction cost can be partially or even wholly offset by the reduced capping cost of the CAD facilities. During placement of fine-grained material from a barge into a CAD or LBC, the velocity of the falling dense jet of material creates a considerable amount of momentum. After the jet impacts the bottom, the more dense material quickly settles out. Residual momentum is transferred to a horizontal velocity which carries fine particles out a considerable distance. Data from past LBC projects show that an apron 15 cm (6 in.) or less in thickness typically extends 150 to 300 m (500 to 1,000 ft) or more beyond the edge of the main mound (that portion of the mound capable of being monitored by bathymetry typically with thickness greater than 15 to 30 cm (6 to 12 in.). The volume of cap material required to cover this apron is considerable. The pits walls of a properly designed CAD site should contain this horizontal jet carrying the fine particles and eliminate the apron, thus substantially reducing capping volume and cost. Limited experience and lack of sufficiently sophisticated models make it impossible to predict with a high degree of certainty that the apron will be entirely contained within the CAD pit. However, the Newark Bay Pit, New York Harbor is now being filled. Also, a recently developed numerical model by ERDC, EL, can provide a first-order design for CAD pits to retain the apron with more sophisticated numerical models planned for the near future. This combination combined with monitoring of actual placements should be able to provide a high degree of certainty that the apron will be contained within the pit walls.

Another advantage of the CAD facility is that it can be constructed on a bottom with a slope too steep for LBC.

Contamination levels for sediments considered under the MUDS framework range from those slightly more contaminated than those allowed at PSDDA sites to those nearly in the Dangerous Waste (DW) category. Based on guidance from CENWS and the Washington State Department of Ecology (WDOE), the expected placement methods for this range of materials is as follows. Sediments placed in the LBC site(s) will likely be those that are only slightly more contaminated than the material placed in the PSDDA sites. Material placed in the LBC sites is assumed to be mechanically dredged, placed in barges, transported to the LBC sites, then bottom-dumped. This method of placement, while likely the least costly, allows for some water column losses and for a considerably greater spread of material on the bottom than a CAD site.

For this conceptual design, sediments placed in CAD sites are also assumed to be mechanically dredged, placed in barges, and transported to the CAD site, at which point they will be bottom-dumped. Because of the pit walls, CAD sites are considerably more immune to erosion and limit the bottom spread of material compared to LBC sites. Therefore, CAD sites could be considered for placement of sediments with more contamination than those placed at LBC sites. If the

sediments to be placed in a CAD are sufficiently contaminated that water column effects are deemed to be a concern, then a method to reduce water column losses could be considered.

Several methods are available to reduce contaminated sediment losses to the water column during placement in a CAD. If the sediments were originally mechanically dredged and placed in barges, upon reaching the CAD site these sediments could be either reslurried for pumpdown through a pipeline with a bottom diffuser or mechanically placed into a large tremie tube without a diffuser. If the dredging site is close to the CAD pit (i.e., 1.6 km (1 mile) or less), the contaminated sediments can be hydraulically dredged with a direct pipeline to the CAD site with placement through a diffuser.

Siting Considerations

Site conditions greatly influence the design and operation of LBC and CAD facilities. Siting will be especially important in Puget Sound, since it is considerably different than most estuaries in the United States. Most estuaries are relatively shallow, many are less than 6 m (20 ft) deep and nearly all are less than 15 m (50 ft) deep. In contrast, the unique geological history of northwest Washington has resulted in terrain with a great deal of relief. The area has high mountains and steep slopes. These steep slopes, 1V:6H being typical, continue underwater such that much of the central part of Puget sound has water depths of 150 to 180 m (500 to 600 ft). Many of the side channels are also quite deep.

The 150-m (500-ft) depths and steep bottom slopes will likely limit the available areas for LBC and to a somewhat lesser extent CAD sites. There are, however, some side channels and small bays with water depths of 61 m (200 ft) and less, e.g., Sinclair Inlet and Port Orchard. These shallow areas with less steep side slopes will be the most desirable locations for a CAD or LBC facility. However, these areas are also likely locations for other uses, and thus finding suitable locations will be a considerable challenge. To conduct the preliminary design, some assumptions on siting criteria for depth and bottom slope are needed and are described in the following section.

Minimum and maximum facility water depths

a. *Minimum depth.* For conceptual design of LBC and CAD facilities, the most basic criteria for locating a site are bottom depth and side slope. Determining a minimum site depth is straightforward. Assuming the sediments will be mechanically dredged and transported to the site in a barge, the minimum water depth is the maximum draft of the barges, e.g., 5.5 to 7 m (18 to 23 ft), depending on barge size plus some safety factor. Thus, a reasonable minimum depth for a CAD site using barge transport of material is 7.6 to 9 m (25 to 30 ft). For an LBC site, the height of the contaminated mound and cap must be included. Assuming a minimum

thickness of 3 m (10 ft) for contaminated mound and cap combination makes the minimum depth of an LBC site 10.7 to 12 m (35 to 40 ft).

It should be noted that the tide range in Puget Sound could reduce the minimum water depths for LBC and CAD sites. Puget Sound has mixed semidiurnal tides, with two unequal high and low tides every 25 hr. The mean tide (difference between average high and low tides) ranges from 1.6 m (5.1 ft) in Bellingham to 2.5 m (8.3 ft) in Olympia, with the average maximum daily tidal range (difference between the extreme daily tides) varying from 2.6 m (8.5 ft) in Bellingham to 4.5 m (14.6 ft) in Olympia. Scheduling placement of sediments to occur around high tide could reduce the minimum required depth from 1.5 to 2.4 m (5 to 8 ft), based on average tides (allowing two placement windows per day) and between 2.4 and 4.3 m (8 and 14 ft) (allowing one placement per day).

b. *Maximum depth.* Deciding on a maximum depth is more complicated. A report by Wiley (1995) has shown that definable mounds can be constructed in water depths of 91 m (300 ft) and greater. In fact, two of the sites described in the report, Elliott Bay (101 m (330 ft)) and Port Gardner (140 m (460 ft)), are in Puget Sound. Therefore from a depth standpoint, much of Puget Sound is a potential site for an LBC facility. Experience gained by New England District (NAE) provides insight on the ability to conduct deepwater capping projects. NAE has conducted two capping demonstrations in deepwater and is planning a third. One small capping project was conducted by the New England District in water depths of 61 m (200 ft) in 1991 and 1992 (Wiley 1996). The project was placed in the Portland Disposal site, located offshore of Portland, ME. The Portland Disposal site is a 1.9-m (1-n. m.) square box, consisting of a flat sandy valley with an average depth of 61 m (200 ft) surrounded by rocky outcrops with depths as shallow as 140 m (138 ft). In this project, 13,000 cu m (17,000 cu yd) of fine-grained dredged material unsuitable for open water disposal (elevated levels of PAHs and metals) were mechanically dredged, transferred into barges, and placed in the Portland Disposal site between October 1991 and January 1992. The unsuitable sediments were capped with 37,000 cu m (49,000 cu yd) of dredged material, also mechanically dredged and transported by barges, between January and June 1992. The cap material came from two projects, 19,000 cu m (25,000 cu yd) of predominantly fine-grained material and 18,000 cu m (24,000 cu yd) of sandy sediments, placed at the same time.

The amount of control used on the placement activities and the extent of the monitoring effort for this project was commensurate with the volume and toxicity of the contaminated sediments. Disposal control was by a Coast Guard nontaut moored buoy, and barge locations were recorded as a given distance from the buoy supplemented by LORAN C positions. Contaminated sediments were placed in an approximately 152-m- (500-ft-) diam circle north of the buoy. Capping sediments were placed over an area roughly 457 m (1,500 ft) across and centered on the contaminated sediment placement area.

A preproject baseline survey and postcontaminated sediment placement surveys were not conducted, therefore a precise identification of contaminated mound footprint was not available. A postcap placement monitoring effort, conducted in July 1992, consisted of bathymetry, sediment profile image (SPI) survey, acoustic sediment density measurements, and sediment sampling for chemistry and grain size. The mix of cap material types made it difficult to precisely identify the cap material, and bathymetry difference maps showed a 0.76-m- (2.5-ft-) thick mound was created. Sediment chemistry data from the cap surface indicated the cap was effectively isolating the contaminants, though precise estimates of cap thickness (target thickness was 30 cm) and coverage could not be made because of the level of monitoring and the heterogenous cap.

This project should be viewed as a moderately successful project. The primary value is that it shows a capping project has been conducted in water depths of 61 m (200 ft). It also shows the need for a thorough monitoring program to accurately define the contaminated mound footprint and cap thickness.

The limitations associated with the 1991/1992 project at the Portland Disposal site, prompted New England District (NAE) to conduct a more rigorous capping demonstration in 1995 to 1997 (SAIC in preparation). For this effort, sediments suitable for ocean disposal from Royal River were separated into two portions. Because the sediments were of similar grain size, the different portions were identified by different microfossils present in each sediment portion. For this effort a preplacement baseline bathymetric survey was conducted, followed by placement of 40,000 cu m (51,700 cu yd) of the pseudocontaminated sediment, again using mechanical dredging and barge placement. A taut moored buoy was used to allow the material to be placed in a tight mound close to the buoy, barge positions were recorded with microwave or DGPS positioning. Post-pseudocontaminated sediment monitoring consisted of bathymetry, soil parameter interaction (SPI), and cores. The pseudocontaminated mound was then capped with 22,000 cu m (29,000 cu yd) of the remaining sediments, also mechanically dredged and barge placed. Postcap placement monitoring consisted of bathymetry and cores. The final report on the monitoring effort should be available in the summer of 1998. Preliminary indications are that the capping was successful, though the similarity in grain sizes made distinguishing between the two sediment groups somewhat more difficult than normal capping projects.

A third deepwater capping project using sediments suitable for ocean disposal is being planned by NAE for the late summer and fall of 1998. Dredging of Cohasset Harbor, Massachusetts, will produce roughly 15,000 to 31,000 cu m (20,000 to 40,000 cu yd) of fine grained inner harbor sediments and 15,000 to 31,000 cu m (20,000 to 40,000 cu yd) of coarser sediments from the outer harbor. The sediments will be placed in the Mass Bay disposal site in water depths of about 91 m (300 ft). The fine-grained inner harbor sediments will become the pseudocontaminated sediments and will be capped with the more coarse-grain sediments from the outer harbor. Dredging, placement, position control, and monitoring will be almost identical to the 1995 to 1997 Portland

Capping Demonstration project. Documentation of these last two projects should provide a considerable increase in confidence that capping in depths greater than 31 m (100 ft) is very possible.

Placing material in an LBC facility located in the 152- to 183-m (500- to 600-ft) water depths of central Puget Sound has some advantages and a number of disadvantages. The first advantage is that the size of the area covered by depths of 152+ m (500+ ft) is considerable, potentially facilitating the location of a suitable site. Second, there may be fewer resources of concern on the bottom of the central deeper parts of the sound. Also, because of the great depths, potential to erode the caps is probably less than at shallower depths. At a site in 152 m (500 ft) of water, wave activity is a nonfactor. Studies of currents and other PSDDA siting activities to locate nondispersive sites should be able to be used for siting.

LBC sites in the more than 152-m (500-ft) depths of Puget Sound have a number of disadvantages. First, the area covered by the contaminated sediment mound in deep water will be greater than that of a mound in shallower water. As the water depth increases, the time for dredged material to fall increases with a corresponding increase in the amount of water entrained. This makes the sediment cloud at impact larger, thus covering a wider area. Therefore, the amount of cap required for a given amount of material will very likely be higher for deeper LBC facilities, increasing costs. The deeper water also provides additional fall time allowing additional fine-grained material to be stripped off the main descending jet. The deeper depths will increase settling time of the stripped particles, allowing them to be spread over a wider area.

Quantifying the amount of additional fine-grained material stripped from a placement in say 31 to 61 m (100 to 200 ft) versus a placement in 152 m (500 ft) with present numerical models is likely to have a considerable amount of uncertainty, though limited actual data may provide some indication of the increase. Perhaps the greatest impediment to siting an LBC at depths of 152+ m (500+ ft) or more is public perception that the material will be spread over the entire sound. However, if siting shallower sites is extremely constrained, a deep site may be considered for material that is only slightly above the contaminant level allowed for unrestricted PSDDA placement. A risk assessment associated with the placement of mildly contaminated sediment in a 152-m (500-ft) site where only 90 to 95 percent of the material is capped may provide some additional insight on the viability of this option.

Limiting LBC sites to a maximum of 31 m (100 ft) seems overly restrictive because the amount of area with depths of 31 m (100 ft) or less is so small that siting an LBC facility would be extremely difficult. Numerical modeling simulations and the ability to create mounds in depths of nearly 152 m (500 ft) indicate that capping at depths much greater than 31 m (100 ft) is technically feasible. Therefore, based on discussions with CENWS, LBC facilities will be limited to a maximum water depth of 61 m (200 ft) for the conceptual design. The 61-m (200-ft) limit provides a reasonable compromise between providing a sufficiently large area to make siting practical and safety.

If some portion of the CAD facility is created by dredging, the maximum depth is limited to the range of existing dredges. Mechanical dredges can dredge to greater depths by simply increasing the length of the wire attached to the bucket. However, cycle time is increased, raising costs and accuracy is reduced. For this conceptual design, a practical maximum depth of 30.5 m (100 ft) is assumed for the bottom of a CAD pit constructed through dredging . This 30.5-m (100-ft) depth is also reasonable from the standpoint of ease of placement of contaminated sediments using pipelines and diffusers.

Maximum bottom slopes

For LBC facilities, the maximum bottom slope is assumed to be 1:100 (1 percent or 0.01 rad (0.6 deg)). This is based on experience with the 1997 LBC project conducted by USAED, New York. Portions of the contaminated material were placed on a bottom with a slope of 0.01 rad (1 deg) (1:60). A slope adjustment occurred after the material was placed to a height in excess of 3.7 m (12 ft). Geotechnical engineers examining the data concluded that the existing bottom slope may have contributed to the slope adjustment. Thus to be more conservative, a 1:100 slope was selected for the MUDS conceptual design. Maximum thicknesses of the LBC mounds were also limited to 2.4 m (8 ft) or less. Because different professions express slope differently, Table 7 was created to show how the three most commonly used units for expressing slope compare for a range of values.

Table 7
Range of Slopes Considered for LBC and CAD Facility Design Expressed in Three Different Units

V:H	Percent	Degrees	V:H	Percent	Degrees
1:200	0.5	0.3	1:20	5.0	2.9
1:100	1.0	0.6	1:15	6.7	3.8
1:60	1.7	1.0	1:10	10.0	5.7
1:50	2.0	1.1	1:6	17.0	9.5
1:40	2.5	1.4	1:5	20.0	11
1:33	3.0	1.7	1:3	33.0	18
1:30	3.3	1.9	1:2	50.0	27
1:25	4.0	2.3	1:1	100	45

For CAD pits, a steeper slope is allowable because a slope adjustment will be contained by the pit walls. Slopes of between 3 and 6 percent (1:33 and 1:16.7) are considered reasonable. For this design, the lower value of 3 percent was selected. If siting constraints makes finding a site with 3-percent slope difficult, the 6-percent value could be considered. A brief review of National Oceanic

and Atmospheric Administration (NOAA) Chart 18440 (1995), which covers all of Puget Sound, showed that a large percentage of the slopes from the waterline down to the deeper portions of the Sound had slopes of 18 percent (1:6.3). If deep pits, i.e., 9 m (30 ft) or more are considered viable, CAD facilities on these steeper slopes could be considered. Note that a dredged CAD is assumed to be constructed with a level bottom, thus the actual bottom slope is of less importance. On a steep slope, constructing a "U"-shaped berm around the sides and downslope edge of the pit to contain the dredged material will be required (Figures 28 and 29).

Volumetric Capacity and Placement Rates

The most basic criteria for LBC and CAD design are the volume of material that will be placed in the facility and the rate at which that material will be placed. Guidance from NWS and Washington State indicates that two-volume and rate assumptions should be used for the conceptual design. The large-volume assumption is 1,500,000 cu m (2,000,000 cu yd) placed over 10 years, which is equal to a rate of 159,000 cu m/yr (200,000 cu yd/yr). The small-volume assumption is 380,000 cu m (500,000 cu yd) placed over 10 years, which is equal to a rate of 38,000 cu m/yr (50,000 cu yd/yr). However, these volumes do not take into account sediment bulking during dredging.

Sediment bulking at LBC and CAD Facilities

The volumes provided by NWS and Washington State are assumed to be in situ, or predredging, volume. During dredging, additional water is added to increase the overall volume of the sediments. This increase in volume during dredging is commonly referred to as bulking. Bray, Bates, and Land (1997) estimate that during mechanical dredging the as-dredged volume will bulk from 10 to 40 percent over the in situ volume. A study of mechanically dredged maintenance sediments from New York Harbor (Tavolaro 1982, 1984) showed an average bulking of 18 percent. A CAD project now being conducted in Boston Harbor is using a 20-percent bulking factor for computing CAD cell volumes. For this LBC and CAD conceptual design, a bulking factor of 20 percent is assumed for mechanical dredging. If techniques other than those commonly used for normal mechanical dredging are used, e.g., environmental buckets and no barge overflow, then this bulking factor should be reexamined. Recent experience with the Boston Harbor CAD and NWS experience on bulking should be reviewed during detailed design.

While the sediments in the barge experience bulking, some of the bulking is reduced when some of the loosely bound water is released during the placement process. The net bulking of sediments as placed on the bottom is often less than the as-dredged bulking in the barge; however this is more difficult to quantify. For conservatism, no loss in volume after placement in a LBC site will be assumed.

If material considered for CAD placement is sufficiently contaminated that water-column losses are a concern, hydraulic dredging could be used with placement via a pipeline, tremie tube, and diffuser to reduce losses. In typical hydraulic dredging, bulking of up to 400 percent is not uncommon as a result of the large amounts of water added to aid in pipeline transport. However, for this application, if hydraulic dredging of contaminated sediments with a direct pipeline connection to the CAD is used, specialized environmental hydraulic dredges will be required. New environmental hydraulic dredges are able to dredge with much less added water, resulting in estimated bulking of 30 percent (PIANC 1996). Therefore, for this conceptual design, a 30-percent bulking of sediments placed in the CAD pits is assumed. Over time, these sediments will very likely consolidate. Depending on the volume and rate of material placement, additional capacity will be realized as the water added during bulking is expelled. However, this process takes time. For future designs where hydraulic placement is considered, CAD volumes could be based on 30-percent bulking.

Another method to place sediments in the CAD is hydraulic unloading of a barge of mechanically dredged sediments. As noted earlier, the fluidized sediments would be pumped down a pipe for placement through a diffuser. While the pipe reduces water-column losses compared to conventional bottom dumping, this method does provide some risk of water-column losses as a result of splashing and air losses because of volitization. Bulking estimates for barge reslurrying are not readily available, though representatives from the Hart Miller or Craney Island CDF could be consulted. Additional information would be needed before choosing a bulking factor for this method of placement.

Revised volumes including bulking

In this conceptual design phase, 38,000 or 150,000 cu m (50,000 or 200,000 cu yd) per year (predredging volume) could be placed in an LBC or CAD site. With the bulking factors mentioned above, this volume will be increased by 20 to 30 percent, or 46,000 and 180,000 cu m/yr (60,000 and 240,000 cu yd/yr) for LBC and 50,000 and 200,000 cu m/yr (65,000 and 260,000 cu yd/yr) for CAD.

Integrating the annual volume of contaminated sediments, conceptual designs for facilities capable of containing total volumes corresponding to 10 years of receiving each of the annual volume will also be provided, i.e., LBC sites with total capacities of 460,000 cu m (600,000 cu yd) and 1,800,000 cu m (2.4 M cu yd) and CAD pits with total capacities of 500,000 cu m (650,000 cu yd) and 2,000,000 cu m (2.6 M cu yd). These volumes do not take into account consolidation.

Consolidation

Depending on the percentage of fine-grained material, it's initial void ratio, the thickness of the layer placed, and the thickness of the cap, the sediments within the CAD will consolidate as the pore water is squeezed out as a result of the applied load. The process of consolidation is relatively slow. Overall consolidation can be on the order of 30 percent or more, with as much as 25 percent of the total consolidation occurring over a period of 6 to12 weeks. For CAD facilities of sufficient depth where material will be placed over multiple years, the additional capacity and resulting cost savings realized by consolidation should be considered in the detailed design. However, without additional data on the geotechnical properties of the sediments planned for placement or the exact configuration (i.e., thickness) of the CAD facilities, consolidation will be ignored for the conceptual design.

Now that the physical properties have been discussed and basic assumptions have been made, the conceptual designs will be developed. However, a scheduling of projects has a profound impact on the conceptual design. Therefore, the placement scheduling will be discussed first.

Scheduling/management

How projects are scheduled will have a major impact on conceptual design, operation, and management of both LBC and CAD facilities. Projects can be scheduled several ways:

a. Individually.

b. Collectively (several together).

c. Seasonally/annually (all the projects that will go to a particular site in a given season or year).

Because capping will be required to start 2 to 4 weeks after placement, considerable reductions in the amount of cap volume required can be realized by scheduling the projects consecutively such that the next project starts within the time limit between projects. The 4-week time limit recommended by Palermo et al. (1998) will be used. This 4-week limit is based on the fact that it takes about 4 weeks for a sufficient number of organisms to be recruited and to bioaccumulate any contaminants such that there is any potential for transfer of contaminants to commercially viable populations of higher organisms. Projects placed consecutively so that the 4-week limit is not exceeded and thus intermediate caps are not required will be termed back-to-back projects.

Projects scheduled individually, i.e., a subsequent project is not expected within 4 weeks, will be required to place an intermediate cap, if not a full cap. Because of the width of the apron, small projects require much higher cap volume to contaminated sediment volume ratios. This will require greater

amounts of cap material and will increase the cost of individual projects, where each project sponsor is assumed to bear the full cost of capping his project.

Our recommended scheduling is to place projects consecutively over a season or year. All the projects will have to be coordinated and planned the prior year or at least several months in advance of the start of dredging. Also, a minimum volume for a year or season's worth of dredging might be considered, i.e., 38,000 to 76,000 cu m (50,000 to 100,000 cu yd). Advance planning will help to ensure a minimum capping cost for each project and will maximize the potential to coordinate the capping project with a maintenance dredging project. However, because of potential difficulties in awarding a maintenance dredging project, an emergency source of capping material must be identified for each project and the appropriate contractual steps taken such that the emergency capping material can be placed if the maintenance material is not available. Ideally, the emergency capping sediments would be located near the LBC facility. Project sponsors jointly share cost of the cap, probably in proportion to the amount of contaminated sediments dredged.

While multiyear planning would be the most advantageous, the level of planning, coordination, and uncertainty involved would make this option impractical. Still some long-term planning is worthwhile.

LBC Conceptual Design

This section begins with a short description of an LBC project recently conducted by the USAED, New York, at the Mud Dump Disposal Site to provide some perspective on actual LBC projects. The LBC conceptual design for MUDS follows.

1997 Mud Dump LBC Project

The largest LBC capping project in the United States was conducted in 1997 by the USAED, New York, and the Port Authority of New York and New Jersey at the Mud Dump site east of northern New Jersey (Clausner et al. 1998). In this project, 535,000 cu m (700,000 cu yd) of mildly contaminated fine-grained sediments were mechanically dredged, transported to the site in barges, and placed in water depths of 23 to 25 m (75 to 82 ft) in about 2 1/2 months. The overall project consisted of three individual projects scheduled to take place consecutively. The sediments were classified as contaminated based on limited potential to cause bioaccumulation of dioxin. The USAED, New York, and USEPA Region 2 have a stricter standard for dioxin bioaccumulation than national guidance and require capping of sediments that show bioaccumulation of >10 parts per trillion (pptr).

The desire to maximize site capacity and allow no apron material to exit the site boundary resulted in placing all the material in a rectangular area 244 by

427 m (800 by 1,400 ft). This resulted in a mound that was initially 3.7 to 4.3 m (12 to 14 ft) tall in some locations with side slopes of up to 0.09 rad (5 deg) (1V:11H). These steep slopes were not stable and, over a few weeks time, slope adjustments occurred over two sections of the mound, which lowered maximum mound elevations to approximately 2.4 to 3.1 m (8 to 10 ft). The footprint of the mound extended an average of 341 m (1,120 ft) beyond the placement area. The apron, with a thickness of 0.15 m (0.5 ft) or less, extended an average of 160 m (525 ft) beyond the placement area. After placement of the contaminated sediments, approximately 1,500,000 cu m (2.0 M cu yd) of 0.4-mm sand was placed using primarily split-hull hopper dredges. The hulls of the hopper dredges were cracked 0.304 m (1 ft) while moving at approximately 2 knots to allow sprinkling of the capping sediments (i.e., particle settling).

Managing placement of the contaminated sediments was greatly facilitated by the use of an automated barge surveillance system, called the New York Disposal Surveillance System (NYDISS) (Pace, Dorson, and McDowell 1998). NYDISS consists of a compact battery powered data logger and logic card connected to a GPS and DGPS receivers and a draft sensor. Using NYDISS, the locations of the barge placements were recorded with an accuracy of ± 0.17 m (±5 ft). Predictions of the mound configuration and display of the NYDISS data were made using the Disposal Area Network for New York (DAN-NY), a commercially available GIS customized for managing the Mud Dump site. The combination of NYDISS and DAN-NY proved to be invaluable for management and operational control of the project.

Other good summaries of capping experience in the United States can be found in SAIC (1995a,b) which describes in detail experience from the USAE District, New England, and a USAEWES capping guidance technical report (Palermo et al. 1998).

LBC considerations for Puget Sound

Designs for LBC facilities based on annual placement volumes of 46,000 and 183,000 cu m (60,000 and 240,000 cu yd) were conducted. It was assumed that a single mound would be created each year, i.e., that scheduling of material placement would be such that intermediate caps would not be required. Using the dimensions realized from the USAED, New York, capping project of 1993 as a basis, three mound sizes were computed based on the annual volumes noted above. Figure 30 shows the 46,000 cu m (60,000 cy yd) mound. Table 8 lists the dimensions.

Table 8
LBC Mound Geometry as Computed by Mound Designer Algorithm in DAN-NY

Volume	Overall Height/ Diameter	Crest Diameter	Inner Flank Height/Width/ Slope	Outer Flank Height/Width/ Slope	Apron Height/Width/ Slope
60,000 cu yd	3.2 ft 2,000 ft	290 ft	1.2 ft 42 ft 1:35	1.5 ft 320 ft 1:215	0.5 ft 500 ft 1:1,000
240,000 cu yd	7.5 ft/ 2,835 ft	395 ft	4.5 ft 158 ft 1:35	2.5 ft 538 ft 1:215	0.5 ft 525 ft 1:1,050

Note: To convert cubic yards to cubic meters, multiply by 0.7645549; feet to meters, multiply by 0.3048.

Actual cap design requires examining each of the components that comprise the cap design thickness. These components include thicknesses to account for physical isolation, bioturbation, erosion, and consolidation. For the purposes of conceptual design, the final cap is assumed to be 0.9 m (3 ft) thick.

The cap volume requirements will vary considerably depending on how the 0.9-m (3-ft) cap thickness is applied. The first decision is whether or not the full cap thickness must be applied everywhere or just an average of 0.9 m (3 ft). Experience with recent capping projects conducted by the USAED, New York, has shown that requiring the full 0.9-m (3-ft) cap everywhere requires an additional 25 percent more cap volume than a cap with an average thickness of 0.9 m (3 ft). The next major decision is whether or not to apply the full cap over the apron. Because the apron has a limited volume of contaminated material and because the material is likely to be only slightly more contaminated than that allowed for unconfined open water disposal, placing a less thick cap over the apron may provide a sufficient level of protection at a substantially reduced cost. Research by ERDC for the USAED, New York, on a particular sediment containing low levels of dioxin, showed that a 2:1 cap to contaminated sediment thickness ratio was sufficient to bring bioaccumulation levels down to acceptable levels (McFarland 1995). Similar research could be conducted for the MUDS project.

Table 9 shows how the cap volumes vary for several different capping requirements. When the volumes based on an average cap thickness are calculated, the average is assumed to apply both to the main mound and apron. Similarly, when the volumes based on a full cap thickness are applied, the volumes are increased by 25 percent, with this increase applying both to the main mound and apron. For example, on the 46,000-cu m (60,000-cu yd) mound, cap volume ranges from 375,000 cu m (490,000 cu yd) with a full 0.9 m (3 ft) everywhere over the main mound and apron, to 153,000 cu m (200,000 cu yd) for an average 0.9-m (3.0-ft) cap over the mound and an average 0.305-m (1.0-ft) cap over the apron. Over 140 percent more cap is required for the most conservative option. Greater ranges in cap volume can be seen for the

183,000 cu m (240,000-cu yd) mound, though the percentage differences are smaller. Note that to determine the overall cap volume required for the 10-year period, the volumes have to be multiplied by 10.

Table 9
Annual Cap Volumes Required for Various Capping Options

Mound Volume (k cu yd)	Mound Outer Diam (ft)	Apron Width (ft)	Main Mound Diam (ft)	Cap Volume 3.0-ft Avg (K cu yd)	Cap Volume 3.0 ft Full (K cu yd)	Cap Volume 3.0-ft Avg 1.0-ft apron (K cu yd)	Cap Volume 3.0 ft Full 1.0-ft apron (K cu yd)
60	2,020	500	1,020	390	490	200	250
240	2,840	530	1,790	750	940	460	570

Note: To convert cubic yards to cubic meters, multiply by 0.7645549; feet to meters, multiply by 0.3048.

It was also assumed that all 10 mounds, for 10 years of placements, would be located adjacent to each other. While the circular mounds could be arranged in a variety of patterns, because the Sound and side channels tend to be long and narrow, a rectangular pattern two mounds wide and five mounds long was selected (Figure 28). Table 10 shows the overall area required by a rectangular box surrounding all the mounds (i.e., square corners). Note that numerical values have been rounded to two significant figures.

Table 10
Dimensions of LBC Facilities to Contain 10 Years of Contaminated Sediments

Annual Capacity (As Placed)/10-Year Capacity	Overall Length	Overall Width	Overall Area
60,000 cu yd 600,000 cu yd	10,200 ft 1.7 n.m.	4,000 ft 0.7 n.m.	940 acres 1.2 sq n.m.
240,000 cu yd 2.4 M cu yd	14,200 ft 2.3 n.m.	5,700 ft 0.9 n.m.	1,850 acres 2.1 sq n.m.

Note: To convert cubic yards to cubic meters, multiply by 0.7645549; feet to meters, multiply by 0.3048; nautical miles to meters, multiply by 1,852; acres to square meters, multiply by 4046.8; square nautical miles to square meters multiply by 3.430×10^6.

One option that could be exercised to reduce the overall bottom area required would be to allow the aprons of adjacent mounds to overlap. Table 11 shows the reduced bottom area required for the LBC facility based on overlapping aprons. The reductions range from over 42 percent for the 46,000 cu m (60,000 cu yd) mounds to 22 percent for the 183,000 cu m (240,000 cu yd) mounds. If the aprons were larger or some overlap of the outer flanks was allowed, the reduction in bottom area realized would be increased.

Table 11
Dimensions of LBC Facilities to Contain 10 Years of Contaminated Sediments with Overlapping Aprons

Annual Capacity (As Placed)/10-yr Capacity	Overall Length	Overall Width	Overall Area
60,000 cu yd 600,000 cu yd	8,100 ft 1.3 n.m.	3,500 ft 0.6 n.m.	660 acres 0.8 sq n.m.
240,000 cu yd 2.4 M cu yd	12,100 ft 2.0 n.m.	5,100 ft 0.8 n.m.	1,430 acres 1.7 sq n.m.

Note: To convert cubic yards to cubic meters, multiply by 0.7645549; feet to meters, multiply by 0.3048; nautical miles to meters, multiply by 1,852; acres to square meters, multiply by 4046.8; square nautical miles to square meters multiply by 3.430×10^6.

Cap material

While not required at this time, a decision on the sediments used for the cap is needed. Successful caps have been constructed of sand and sand/silt/clay mixtures. For sand caps, the larger the grain size of the sediments, the more resistant the cap to erosion. Erosion of a sand cap is also more easily predicted than a cap with significant percentages of fines. Predicting erosion of caps with significant fine-grained components can be done but requires specialized analysis of the specific sediment in question and will depend on the dredging method and method of placement. Initial indications from NWS are that primarily sandy clean sediments are desirable for capping. The Snohomish River, Swinomish Channel, Puyallup River, and Duwamish River have been suggested by NWS as sources of cap material. If maintenance dredging does not provide a sufficient volume of sediments for capping, then other, probably more costly, sources of cap material would have to be considered.

Contaminated sediment dredging, transportation, and placement

As noted earlier, the contaminated sediment is assumed to be dredged mechanically, placed in bottom-dump barges, transported to the LBC site by tugs, then released. To create the mound of the desired geometry, tight control on barge location will be required. Details on how to accomplish this are discussed in the section on operational controls.

Mixing zones. The boundary of the mixing zone defines the point of compliance with water quality standards or biological standards tied to the potential water-column release associated with placement operations. For the purposes of conceptual design, the boundary is assumed to extend 305 m (1,000 ft) beyond the placement area (typically equivalent to the mound crest dimensions).

Cap placement. For this conceptual design, a sand cap is assumed with placement by barge using a cracked hull with two tugs to spread the cap evenly

over the mound. This method of placement has been used successfully on a number of projects in Puget Sound (Sumeri 1996). Placement of sand caps using a hopper dredge with a cracked hull or direct pump out through over the side pipes is also a viable option.

CAD Conceptual Design

General considerations

As noted earlier, CAD provides a higher level of protection than does LBC, with reduced water-column losses and almost no potential for erosion. Also, they should be more immune to a seismic event. Two basic types of CAD facilities are envisioned for the conceptual design. First, is a one-time CAD. A one-time CAD is large (aerially) and sufficiently deep that multiple years of placement can occur within the single CAD, with each succeeding increment (year or season) of material placed on the top of the preceding increment (Figure 31). Intermediate cap layers are required after dredging each year or season. While it may not be practical to create a single CAD facility to handle all 10 years of contaminated sediments, it may be more practical to design a CAD facility to handle 2 to 5 years worth of materials. The other type of CAD facility envisioned is a sequenced CAD. This type of CAD consists of a series of smaller CAD cells placed next to each other, each capable of holding 1 year or one season's volume of contaminated sediments. The following paragraphs discuss the advantages and disadvantages of each method.

A one-time CAD provides the greatest amount of capacity for a given area. Thus, if siting a CAD facility proves to be difficult, perhaps creating a single site as opposed to several sites might be considered. If the area available is limited, then a deep, one-time CAD capable of holding at least 5 and ideally 10 years of contaminated material might be the best option. As noted above, intermediate caps would be required after each year or season of dredging. However, these intermediate caps would most likely not have to be as thick as a final cap (say 0.305 m (1 ft) thick vs 0.914 m (3 ft) thick for a final cap). Thus, compared to a sequenced CAD which would require a full cap at the end of each year, a one-time CAD of equal capacity should require considerably less cap than a sequenced CAD (note that if the material from the adjacent cells of a sequenced CAD are suitable as cap material then this advantage of a one-time CAD is not realized). Also, because the entire volume of a layered CAD would be dredged at one time, the overall cost of dredging could be less than for a compartmentalized CAD which would have to pay for dredge mob/demob each year. Another advantage of a layered CAD is that the tall pit walls provide a greater factor of safety against material escaping over the pit walls initially. During initial placements, monitoring can be used to determine how far up the pit walls the material climbs. This should allow the determination of the final placement elevation and development of placement techniques and predictive models to reduce the potential for material to escape.

A one-time CAD facility also has a number of disadvantages when compared to a sequenced CAD. Perhaps the biggest disadvantage is the high first cost. While the mob/demob cost for a sequenced CAD will likely be somewhat higher, obtaining funding for a single year's worth of dredging might be much easier. A second disadvantage is that should policies change over time, all the capacity might not be used. With a sequenced CAD, planning for the next year's dredging should be finalized before the end of the present dredging season. Thus, dredging just the required capacity is possible, likely making the most efficient use of limited funds. Another disadvantage of a one-time CAD is that it would be almost impossible to remove a lower layer at some future time. With a sequenced CAD, it would be straightforward to remove the material in a single cell for treatment if a future advance in technology makes it feasible.

During creation of a CAD site, sediments could be stockpiled nearby for redredging and placement as cap material. Excess material beyond what is needed for capping would likely be placed in the nearest appropriate PSDDA site. The possibility of using the excess CAD pit material beneficially could also be examined, but is beyond the scope of this report. If the sequenced CAD option were used, the initial cell could be dredged with material going to create confining berms, beneficial uses or a PSDDA site. After the first cell is filled with contaminated sediments, excavation of the second cell would begin. Ideally, at least some portion of this material would be suitable as cap material for the first cell. Because the second cell is adjacent to the first cell, the material could either be mechanically dredged and placed in barges for transfer and placement or hydraulically dredged with transfer by direct pipeline and diffuser. Excess material beyond what is needed for capping would go to confining berm construction, beneficial uses, or a PSDDA site. For berm construction, beneficial uses, or PSDDA site disposal, mechanical dredging with barge transfer is preferred. For the one-time CAD cells, the material removed that is suitable as cap material will have to be stockpiled (a considerable volume) then redredged for use as cap. This will involve a considerable expense.

Even with the added confinement provided by the pit walls, some small loses of material will occur. If material is transferred to the bottom via pipeline, then the potential for losses should be very small, because of some minor leakage from the joints or from splashing if the material is fluidized in the barges for pumpdown. If conventional bottom placement from barges is used, then a small percentage of material will be released. During cap placement, these small amounts of sediment will be covered by the cap as it moves beyond the cell boundary, probably on the order of several inches or more of cap material. For the conceptual design, additional capping of the contaminated material beyond the cell lip will not be required.

CAD cell options

Two sets of conceptual designs for CAD pits were developed, one for the multiple cell-sequenced CAD and a second set for the one-time CAD. The sequenced CAD designs were based on cells 11 m (35 ft) deep with 1:3 side

slopes. The one-time CAD designs had the same side slopes, but two cell depths were investigated, 11 and 17 m (35 and 55 ft). The 17-m (55-ft) depth was included because the 11-m (35-ft) limit made the area covered by these cells quite large. A much wider range of CAD depths, say 6 to 23 m (20 to 75 ft) could be done, but time limited this study to the two values. Note, if geotechnical data from borings indicate more steeply sloping cell walls are possible, the volume contained in each pit will increase as the slope becomes steeper. Cell volume will also increase as cell depth increases. A cross section of the CAD cells is shown in Figure 31.

Because the waterways in Puget Sound tend to be narrow, the shape selected was a rectangle for most cases. The minimum width of a cell was 91 m (300 ft) or six barge widths. The Boston Harbor CAD used minimum CAD cell widths of 31 to 61 m (100 to 200 ft). However, the water depths in Boston Harbor are fairly shallow, 11 to 13 m (37 to 42 ft). Because the depths where the CAD cells could be sited could be up to 31 m (100 ft) deep, the minimum width was increased to 91 m (300 ft). The minimum length of a CAD cell was assumed to be 152 m (500 ft) or two barge lengths. If conventional bottom placement from barges is used with sediment placed in the CAD, it was assumed that the barges would be nearly stationary. Thus, the 152-m (500-ft) minimum length was thought to be adequate. For many of the options, longer cells were used. For most cases, the CAD cells were designed to be twice as long as they were wide.

In the cells, 9 or 15 m (30 or 50 ft) of contaminated sediments were assumed to be placed with a 1.5-m (5-ft) distance between the upper surface of the contaminated surface and the pit lip. It was assumed that the average cap thickness was 0.1 m (3 ft). Because the cap surface in the CAD cells is assumed to be located 0.6 m (2 ft) below the ambient bottom, the potential for erosion should be less. In fact, the depression formed should encourage deposition. For a full 0.9-m- (3-ft-) thick cap everywhere, the cap volumes should be multiplied by 1.25. The 1.5-m (5-ft) lip height is considered to be reasonably conservative, though a more detailed study should be a future effort. A substantial portion of the conceptual design effort culminated in a large spreadsheet. Pertinent data from the spreadsheet are shown as Tables 12 and 13. The principal items of interest in the spreadsheet are the surface area required and cap volumes associated with the various options. If desired, ERDC can supply the spreadsheet in electronic format so NWS can consider other options.

Table 12
Sequenced CAD Cell Design Parameters

Surface Length	Surface Width	Cell Volume Removed	Net Cell Contaminated Sediment Capacity	Net 10 yr Contam Sed Capac	Cap Volume 3-ft Cap	10-Year Cap Volume	Surface Area Single Cell	10-yr Total Surface Area	10-yr Surface Area w/ Berms
480 ft	240 ft	80 K cu yd	60 K cu yd	600 K cu yd	12 K cu yd	120 K cu yd	3 acres	26 acres	59 acres
820 ft	410 ft	300 K cu yd	240 K cu yd	2.4 M cu yd	36 K cu yd	360 K cu yd	8 acres	78 acres	129 acres

Note: To convert feet to meters, multiply by 0.3048; cubic yards to cubic meters, multiply by 0.7645549; acres to square meters, multiply by 4046.8.

Table 13
One-Time CAD Cell Design Parameters, 11-m- (35-ft-) Deep Cells

Surface Length	Surface Width	Cell Volume Removed	Net Cell Contaminated Sediment Capacity	Cap Volume 3-ft Final Cap	Intermed Cap Volume 1 yr	Total Intermed Cap Volume 9 yr	Total Cap Volume Final + Intermed	Total CAD Surface Area	Total Surface Area w/ Berms
1,210 ft	610 ft	730 K cu yd	600 K cu yd	78 K cu yd	20 K cu yd	180 K cu yd	260 K cu yd	17 acres	26 acres
2,250 ft	1,130 ft	2.9 M cu yd	2.4 M cu yd	280 K cu yd	80 K cu yd	730 K cu yd	1,010 K cu yd	58 acres	75 acres

Note: To convert feet to meters, multiply by 0.3048; cubic yards to cubic meters, multiply by 0.7645549; acres to square meters, multiply by 4046.8.

For the sequenced CADs, two cells with the designated single-year capacities, 46,000- and 199,000-cu m (60,000- and 260,000-cu yd) capacities were computed. Examining the information in Table 14 shows that the single 46,000-cu m (60,000-cu yd) CAD cell occupies a surface area of 12 ha (3 acres) and requires a cap volume of 9,000 cu m (12,000 cu yd). Assuming that a 46,000-cu m (60,000-cu yd) cell were created every year for 10 years to realize an overall capacity of 460,000 cu m (600,000 cu yd), this would require a total area of 11 ha (26 acres) and a total cap volume of 92,000 cu m (120,000 cu yd). Note that the surface area for the full 10 years of capacity include no space between the cells for the confining berms. Assuming the site has a sloping bottom, confining berms on three sides are needed to contain material. Assume the width of the confining berms is 46 m (150 ft) as shown in Figure 28. The total surface area required including the 10 CAD cells and confining berms for the 10 years of capacity becomes 24 ha (59 acres). Note that even if the bottom is flat, some distance between adjacent cells will be required. For the conceptual design assume this distance is also 46 m (150 ft).

For the one-time CAD cells, the surface area was increased so that each single cell had the desired 10-year capacity of 459,000 cu m (600,000 cu yd) and 1,500,000 cu m (2.4 M cu yd). Within each CAD cell, a single year's volume of contaminated sediments would be placed followed by an intermediate cap, assumed to be 0.305 m (1 ft) in thickness. In computing the volume of sediments placed in the one-time CADs, the contaminated sediments were assumed to consolidate a sufficient amount (30 percent) such that the volume occupied by the nine intermediate cap layers did not reduce overall capacity. The 30-percent consolidation value was selected based on the assumption that the increase in volume of 20 percent as a result of bulking would be rather quickly eliminated after consolidation, and that an additional 10 percent consolidation would result because the thickness of the sediments placed in the CAD cells was much greater than found in situ. Obviously, consolidation tests on the proposed contaminated material will be needed to more accurately compute an expected consolidation amount.

Tables 13 and 14 show the results of the spread sheet calculations for the one-time CAD cells. The 1,800,000-cu-m (2.4 M-cu yd) contaminated sediment

capacity cell, 10 m (35 ft) deep (last row of Table 15), requires 2,200,000, cu m (2.9 M cu yd) of sediments to be removed. This volume accounts for the 1,800,000 cu m (2.4 M cu yd) of bulked contaminated sediments placed in the pit that over time are assumed to consolidate 30 percent to a volume of 1,300,000 cu m (1,680,000 cu yd), plus the intermediate and final caps plus the 0.61-m (2-ft) depression remaining after the cap is placed. A total of 772,000 cu m (1,010,000 cu yd) of cap material must be provided that consists of nine intermediate 0.305-m- (1-ft-) thick cap layers requiring an average of 61,000 cu m (80,000 cu yd) each and a final 1-m- (3-ft-) thick cap layer requiring 214,000 cu m (280,000 cu yd). The 0.61-m (2-ft) depression intended to remain after the cap is placed amounts to another 143,000 cu m (187,000 cu yd). The total CAD cell surface area is 23 ha (58 acres). When a confining berm on three sides is added, the total surface area is 30 ha (75 acres).

Table 14
One-Time CAD Cell Design Parameters, 17-m- (55-ft-) Deep Cells

Surface Length	Surface Width	Cell Volume Removed	Net Cell Contaminated Sediment Capacity	Cap Volume 3 ft Final Cap	Intermed Cap Volume (1 yr)	Total Intermed Cap Volume (9 yr)	Total Cap Volume Final + Intermed	Total CAD Surface Area	Total Surface Area w/ Berms
1,050 ft	520 ft	700 K cu yd	600 K cu yd	58 K cu yd	12 K cu yd	105 K cu yd	160 K cu yd	21 acres	31 acres
1,870 ft	930 ft	2.7 M cu yd	2.4 M cu yd	190 K cu yd	48 K cu yd	440 K cu yd	620 K cu yd	40 acres	54 acres

Note: To convert feet to meters, multiply by 0.3048; cubic yards to cubic meters, multiply by 0.7645549; acres to square meters, multiply by 4046.8.

The 459,000 cu m (600,000 cu yd) contaminated sediment capacity cell, 11 m (35 ft) deep (next to last row of Table 13), requires 558,000 cu m (730,000 cu yd) of sediments to be removed. This volume accounts for the 459,000 cu m (600,000 cu yd) of bulked contaminated sediments placed in the pit that over time are assumed to consolidate 30 percent to a volume of 320,000 cu m (420,000 cu yd)), plus the intermediate and final caps plus the 0.61-m (2-ft) depression remaining after the cap is placed. A total of 199,000 cu m (260,000 cy) of cap material must be provided consisting of nine intermediate 0.305-m- (1-ft-) thick cap layers requiring an average of 15,000 cu m (20,000 cu yd) each and a final 1-m- (3-ft-) thick cap layer requiring 60,000 cu m (78,000 cu yd). The 0.61-m- (2-ft-) depression intended to remain after the cap is placed amounts to another 41,288 cu m (54,000 cu yd). The total CAD cell surface area is 6.9 ha (17 acres). When a confining berm on three sides is added, the total surface area is 11 ha (26 acres).

Note that the intermediate cap volumes listed in the Tables 15 and 16 are an average. For the initial layers placed at the bottom of the cell, the sloping sides result in a smaller area corresponding to an intermediate cap volume requirement below the average value. Conversely, when the cell is nearly full, the intermediate cap volume requirement will be greater than the average value.

Table 15
Overall Dimensions of CAD Facilities to Contain 10 Years of Contaminated Sediments

Type of CAD/ Cell Depth	Annual Capacity (As Placed)/ 10-yr Capacity	Overall Length	Overall Width	Overall Area
Sequenced/ 35 ft	60,000 cu yd/ 600,000 cu yd	3,300 ft 0.54 n.m.	780 ft 0.13 n.m.	59 acres 0.07 sq n.m.
Sequenced/ 35 ft	240,000 cu yd/ 2.4 M cu yd	5,000 ft 0.82 n.m.	1,100 ft 0.18 n.m.	130 acres 0.15 sq n.m.
One Time/ 35 ft	60,000 cu yd/ 600,000 cu yd	1,510 ft 0.25 n.m.	760 ft 0.12 n.m.	26 acres 0.03 sq n.m.
One-Time/ 35 ft	240,000 cu yd/ 2.4 M cu yd	2,550 ft 0.42 n.m.	1,280 ft 0.21 n.m.	75 acres 0.09 sq n.m.
One-Time/ 55 ft	60,000 cu yd/ 600,000 cu yd	1,350 ft 0.22 n.m.	670 ft 0.11 n.m.	21 acres 0.04 sq n.m.
One-Time/ 55 ft	240,000 cu yd/ 2.4 M cu yd	2,170 ft 0.36 n.m.	1,080 ft 0.18 n.m.	54 acres 0.06 sq n.m.

Note: To convert feet to meters, multiply by 0.3048; cubic yards to cubic meters, multiply by 0.7645549; nautical mile to meters, multiply by 1,852; acres to square meters, multiply by 4046.8; and square nautical miles to square meters multiply by 3.430×10^6.

Obviously, the deeper 17-m (55-ft) cells (Table 14) provide many advantages, reduced cap volumes and reduced surface area, compared to the 11-m- (35-ft-) deep cells. For the 1,800,000-cu-m (2.4 M-cu yd) CAD cell that is 17 m (55 ft) deep, the total volume of material that has to be removed drops from 2,200,000 to 2,100,000 cu m (2.9 M cu yd to 2.7 M cu yd), the surface area required (including berms) drops from 30 (75 acres) to 22 ha (54 acres), and the volume of cap required drops from 772,000 to 474,000 cu m (1,010,000 to 620,000 cu yd).

Overall, the sequenced CAD cells have reduced cap volumes but require a much larger surface area than the one-time CAD cells. For instance, the ten 46,000-cu m (60,000-cu yd) sequenced cells required to obtain 460,000 cu m (600,000 cu yd) occupy an area of 24 ha (59 acres) including the confining berms. For the 11-m- (35-ft-) deep one-time CAD cells, the surface area required reduces to 11 ha (26 acres) (less than one-half that required for the sequenced cell). The 17-m- (55-ft-) deep one-time CAD cell requires even less area, 8.5 ha 21 acres. The total cap volume is 199,000 cu m (260,000 cu yd) for the 459,000-cu m (600,000-cu yd) one time 11-m- (35-ft-) deep cell compared to 92,000 cu m (120,000 cu yd) for the ten 11-m- (35-ft-) deep sequenced CAD cells. For 1,500,000 cu m (2.4-m-cy) capacity, the 11-m- (35-ft-) deep one-time cell requires 772,000cu m (1,010,000 cy) of cap, while the 10 sequenced 183,000 cu m (240,000 cu yd) cells only require 275,000 cu m (360,000 cu yd). The 17-m- (55-ft-) deep one-time CAD cells require considerably less cap than the 11-m- (35-ft-) deep one-time cells but still require more cap than the sequenced cells.

Table 16
Design and Performance Criteria for LBC and CAD Options

Item or Category	MUDS Design/ Performance Standard
Overall design objective	Accommdate the required volume with releases within acceptable limits.
Overall performance objective	Control direct exposure of organisms to the contaminated sediments such that toxicity or unacceptable levels of bioaccumulation do not occur and contaminant migration is controlled.
Engineering design	Design will be completed by competent professional engineers and standard USACE engineering design documents will be applied as appropriate.
Site characteristics	Water depths limited to 300 ft; bottom slopes limited to 6% or less bottom elevations -80 ft to -200 ft MLLW; water column currents will not exceed 1 ft/sec and near-bed velocities will not exceed 0.5 ft/sec during contaminated sediment placement.
Environmental evaluations	Sites evaluated in accordance with the USACE/EPA Technical Framework and USACE capping guidance document.
Pit geometry/ orientation/ release points	Longer dimension (length) oriented along the axis of the predominant tidal or ambient current direction; releases located at the "upstream" end of the pit, depending on the tidal cycle.
Excavated slopes	Safety factor of 1.3 for slope stability is attained; bed stability assessed by competent professional engineers and consider local area sloughing, seismicity, or unusual sediment conditions.
Dredging and placement of contaminated materials	Equipment and methods compatible with conventional dredging methods and accomplished so that the resulting deposit can be defined by monitoring and effectively capped; mechanical dredge with barge required for LBC option.
Dispersion during placement	Water-column concentrations will not exceed applicable acute water quality standards, and concentrations of suspended dredged material will not exceed applicable water-column toxicity criteria at the boundary of the designated mixing zone.
Retention of materials	LBC full design cap thickness placed over thickness greater than 10 cm and thinner apron cap placed over thicknesses greater than 2 cm; thickness of accumulated material outside the lip of CAD exceeding 2 cm requires apron cap.
Cap material	Cap material must be acceptable for open water placement, as determined under the CWA regulations and PSDDA requirements.
Cap placement	Equipment and placement techniques selected to avoid displacement and cap material will be placed (spread) to gradually build to the design thickness
Positioning	Differential global positioning system.
Interim caps	CAD interim caps required with delay of more than 4 weeks between contaminated material placements; interim cap to consist of a 0.305-m (1-ft-) thickness of suitable material.
Final cap design	In accordance with the latest USACE/EPA guidance and will consist of components for physical isolation, bioturbation, and erosion for 20 years of normal current/wave energies or the design storm event.

Note: To convert feet to meters, multiply by 0.3048.

While Tables 12, 13, and 14 list the overall area required in acres for the various CAD site options, they do not give the overall dimensions. To make the CAD cell options more directly comparable to the dimensions for the LBC options provided in Tables 10 and 11, the overall dimensions were calculated and are listed in Table 15. The dimensions include the confining berms. As for

the LBC facilities, the dimensions for the sequenced CAD cells assume two parallel rows of five cells each similar to Figure 28.

LBC vs CAD - Comparison of cap volumes and surface areas

From the comparisons, it is obvious that the CAD cell options greatly reduce the required surface area compared to the LBC option. The 459,000-cu m (600,000-cu yd) capacity LBC facility will require a bottom surface area of 380 ha (940 acres) (270 ha (660 acres) if aprons overlap), compared to 8.5 to 24 ha (21 to 59 acres) for the various CAD options. The 1,800,000-cu-m (2.4 M-cu yd) LBC facility will require a bottom surface area of 750 ha (1,850 acres) (579 ha (1,430 acres) if aprons overlap) compared to 22 to 53 ha (54 to 130 acres) for the various CAD options.

Similarly, impressive reductions in required cap volume are also realized for the CAD option compared to the LBC options. The 460,000-cu m (600,000-cu yd) LBC facility (ten 46,000-cu-m (60,000-cu-yd) mounds) will require from 1,500,000 to 3,823,000 cu m (2 to 4.9 M cu yd) of cap. The 459,000-cu m (600,000-cu yd) CAD facilities will require from 92,000 cu m (120,000 to 260,000 cu yd) of cap with some to most of the cap volume being created from cell excavation. For the 1,800,000-cu m (2.4 M-cu yd) LBC facility, ten 183,000-cu m (240,000-cu yd) mounds will require from 3,500,000 to 7,200,000 cu m (4.6 to 9.4 M cu yd) of cap. The 1,800,000 cu m (2.4 M-cu yd) CAD facilities will require from 275,000 to 772,000 cu m (360,000 to 1,010,000 cu yd) of cap, once again with some to most of the cap volume being created from cell excavation.

Placement Operations/Equipment

LBC placement

As noted earlier, mechanical dredging of the contaminated sediments into bottom-dump barges with conventional placement was assumed. To achieve the desired mound geometry, the location of each dump will be precisely planned and monitored. Barge surveillance units similar to the NYDISS system described earlier will be required. Barges will have to be almost stationary during disposal. The fine-grained material will exit the barge in a short period of time. DGPS on the barge and tug will be required to precisely and accurately position the vessel. The tug will require a display of both its position and the barge. Depending on water quality issues at the boundary of the mixing zone, placement may be limited to certain stages of the tide.

Placement of capping sediments can be done by a split-hull barge using two tugs to position it or by hopper dredges using cracked hulls or direct pump out through over-the-side pipes. Both methods have a good track record for accomplishing this task. As with the contaminated sediments, DGPS positioning

of the vessels is required along with electronic recording for later display of the data. Use of models to predict the footprint and thickness of the cap, such as STFATE and MDFATE, is recommended.

As a result of the recurring nature of the capping activities, some modifications to existing plant or new plant might be warranted to overcome problems on past projects. For example, a towed barge has limited maneuverability. Powered barges are rare in the United States, but a powered barge might be able to more efficiently cap with its ability to turn over a much smaller turning radius. Directly connecting the tug and barge might be possible if the change in barge draft as the load is placed can be accommodated.

CAD Placement

Placement of contaminated sediments in the CAD sites is assumed to be hydraulically either via direct pipeline with a diffuser from a nearby hydraulic dredge removing contaminated sediments or reslurried material from a barge. For the direct hydraulic placement, a surface barge/platform/vessel will be used to support the vertical pipe with the diffuser on the end. Real-time DGPS position of the barge must be known. Either a sophisticated mooring with the capability to reposition the barge remotely will be needed or a dynamically positioned vessel or sophisticated anchor/winch system aboard the vessel will be required. While this type of an application is rare in dredging in the United States, the technology is routinely used by oil companies working offshore. Thus, application to this type of a situation should have very high probability of success.

If the contaminated sediments are mechanically dredged and placement via conventional bottom dumping is not allowed because of water quality concerns or concerns over material spread, then the material will have to be reslurried for pumpdown to the bottom. The dredging industry routinely uses a modified hydraulic dredge with a specialized ladder to inject water into the barge and then remove it. Typically, these barge unloaders are moored in a protected area. If the barge unloader were positioned directly over the placement site, it would most likely have to be dynamically positioned because a conventional mooring would probably interfere with the tugs and barges with the contaminated sediments. Another disadvantage of positioning the barge unloader directly over the CAD facility is the potential for differential motion between the two vessels. If the CAD site is located where wave activity can be significant, mooring can become difficult and hazardous. Also, the unloading process will become more difficult, with splashing of the contaminants during the fluidizing process becoming more likely.

Another option would be to have a barge loader positioned in a protected area within say 2 km (1 mile) or less of the CAD facility. A submerged pipeline would run from the barge unloader out to the barge/vessel with downpipe and diffuser located over the CAD facility. Tugs could then bring barges with contaminated sediments into the protected area for unloading.

Operational contingencies

The potential for accidents, short dumps, broken pipelines, etc. must be considered when developing operations plans. Procedures on how to handle these contingencies must be worked out in advance. As noted earlier, if sediments from a navigation project are to be used for capping and the capping contract is delayed, then an emergency source of cap material and a contract to have it dredged will be required. This emergency cap could be thinner, say 15 to 30 cm (6 to 12 in.) with the remainder of the cap placed at a later time when the maintenance dredging cap material is available. The permit should require an identified emergency source.

Design and Performance Standards for LBC and CAD

This section provides design standards for MUDS LBC and CAD options. The proposed standards are intended to be applied to a site-specific design should a LBC or CAD option be selected for MUDS. The standards are based on available technical guidance in the literature, as well as available design information from projects nationwide and within Puget Sound. Although the design of a MUDS alternative would not strictly be considered as a functional design as defined under the S-4 standards, the proposed standards in this section are technically compatible with the S-4 functional design standards as appropriate. The standards for various aspects of the design are described in the following paragraphs, and all the proposed standards along with the S-4 standards are summarized in Table 16.

Overall design and performance objectives for LBC and CAD options

The overall design objective for any alternative is to provide a site that will accommodate the required volume of dredged material and will allow placement of the material within the site such that the material is contained and any releases of sediment or associated contaminants are within acceptable limits. The overall performance objective for an LBC or CAD alternative is to control direct exposure of benthic organisms to contaminated sediments such that toxicity or unacceptable levels of bioaccumulation do not occur. An additional performance objective for LBC or CAD sites is the control of contaminant migration through the subaqueous cap as a result of advection and long-term diffusion. These overall objectives require that a cap be placed at a thickness designed to isolate the contaminated sediments from the benthic environment and to control contaminant migration and that the design cap thickness be maintained over the long term.

Site Selection

Site characterisitcs directly influence the design of an LBC or CAD option. Water depth and bottom slope have been proposed as site selection criteria for LBC or CAD sites. Exclusionary criteria have been proposed for LBC sites that would eliminate sites with water depths greater than 61 m (200 ft) and better slopes exceeding 1 percent. Exclusionary criteria have been proposed for CAD sites that would eliminate sites with slopes exceeding 6 percent and with water depths exceeding 31 m (100 ft).

Engineering design procedures

Accepted engineering design procedures and standards must be followed for the design of LBC or CAD projects. The USACE has developed extensive engineering design guidance available in the form of Engineer Manuals (EMs), guide specifications, and various design documents and manuals. The site design will be completed by competent professional engineers. The USACE technical guidance document for subaqueous capping (Palermo et al. 1998) will be used as the basis for design of LBC or CAD options. Standard USACE engineering design documents will be applied as appropriate in the design. A listing of USACE engineer manuals and other design documents is given in EP-25-1-1 (HQDOA 1995b).

Environmental evaluations and contaminant pathway controls

Environmental evaluations conducted as a part of the design will be in accordance with the Technical Framework (USACE/EPA 1992) and the USACE technical guidance document for subaqueous capping (Palermo et al. 1998).

Stability of Excavated CAD Pit and Berm Slopes

Stability considerations for excavated CAD pits and subaqueous berms fall under the current conventional geotechnical design practice and policy of the USACE. Technical guidance for embankment stability is found in EM 1110-2-1902, "Stability of Earth and Rock fill Dams," (HQDOA 1970a). A replacement edition of EM 1110-2-1902 bearing a new manual number is nearing completion under the title, "Shear Strength and Slope Stability". Typically, the most critical stability case for an embankment will be the "after construction" condition for which a minimum factor of safety of 1.3 is mandated.

The potential for slope failure of the excavated pit and berm slopes will likely be greatest immediately following excavation. However, the consequences of localized sloughing are less at this time due to the fact that any contaminated material placed during the early stages of filling would be at a greater depth

within the CAD containment. Design of the slopes of the excavated pit and berm will be set such that a safety factor of 1.3 for slope stability is attained.

Dredging and Placement of Contaminated Sediments

Placement methods and equipment

Selection of equipment and methods for placement of contaminated materials at LBC or CAD sites will be compatible with conventional dredging methods used in the Puget Sound region. Placement of contaminated material prior to capping should be accomplished so that water-column dispersion is minimized and the resulting deposit can be effectively capped (Palermo et al. 1998).

For LBC options, factors such as water depth, ambient currents, and natural bottom topography must be considered in selection of equipment for placement. LBC sites for MUDS will likely be in relatively deep water and will likely have a mildly sloping bottom topography. The use of mechancial dredges and barge placement will be used for LBC contaminated sediment placement. Such methods will result in a tendency for the placed materials to mound rather than flow, resulting in a more compact mound, which is easier to cap.

For a constructed CAD pit, the geometry in the form of a bottom depression defines and limits the extent of bottom spread. Although placement of contaminated materials by hydraulic pipeline and hopper dredge may be acceptable for a CAD pit, placement by barge would be more desirable. Mechanical dredging with clamshell results in materials placed in the transport barges at densities comparable to in situ conditions, and such materials normally exhibit a high degree of cohesion. Placement of mechanically dredged materials by bottom-dump barge would result in less water column dispersion than dredging and placement by hopper dredge.

Dispersion of sediments during placement

The contaminated materials must be placed in the CAD pit such that water-column impacts from releases of contaminants during placement are acceptable. The degree of dispersion and associated water-column contaminant release dictates whether a given discharge is acceptable from the standpoint of water-column impacts. The dispersion behavior exhibited by the material during and immediately following discharge and the deposition of the material as it settles to the bottom must be evaluated to determine the acceptability of a proposed placement method as a part of the overall design (to include equipment, method of placement, rate of placement, and positioning of release points or lanes within the CAD pit). These dispersion and settling processes occur over a time period of a few minutes to several hours for a single release from a barge or hopper dredge.

Evaluation of water-column mixing of released contaminants or suspended dredged material is necessary whenever potential water-column contaminant effects are of concern. Such an evaluation may involve comparison of predicted water-column contaminant concentrations with water quality criteria (or standards) or predicted suspended dredged material concentrations with bioassay test results. Contaminated materials will be placed such that dissolved water-column concentrations will not exceed applicable acute water quality standards at the boundary of the designated mixing zone. Further, the materials will be placed such that the concentrations of suspended dredged material will not exceed applicable water-column toxicity criteria at the boundary of the designated mixing zone. If evaluations of dispersion and release for hopper or barge surface release indicate standards are exceeded, water-column controls such as use of a submerged diffuser, tremie, controlled rate of release, or use of geosynthetic fabric container (GFCs) can be considered.

Retention of materials

The contaminated materials must be placed for LBC and CAD options such that any release of sediment outside the limits of capping is minimized. Available field data on conventional open water disposal operations indicate that the total amount of dredged material dispersed in the upper water-column and transported long distances from the placement area is 1 to 5 percent of the original mass of material (Truitt 1986a). For controlled placement in a CAD pit, the dispersed fraction should be lower than for conventional open water conditions.

For LBC, the extent of the cap can be adjusted to cover an apron deposit. Contaminated materials at thickness exceeding 10 cm should receive the full design cap thickness. As noted earlier, research by WES (McFarland 1995) showed a reduced cap thickness over the apron reduced bioaccumulation of mildly contaminated NY Harbor sediments to acceptable values. Also, an expert panel reviewing bioturbation (Rhoads and Carey 1997) supported McFarland's conclusions for a reduced cap thickness over the apron for some applications. A detailed review of capping effectiveness of several major capping projects conducted by the Corps' New England District (SAIC 1995a,b), where reduced cap thicknesses (20 to 40 cm) were placed over the outer portions of the contaminated sediments mounds, has shown no increased contaminant levels in the biota inhabiting the caps. Thus, depending on the toxicity of the sediment, apron area, and availability and cost of capping sediments, it seems reasonable to consider a thinner cap over the apron. This proportionally thinner cap would be placed over the apron, defined as thickness of 2 to 10 cm. A thickness of 2 cm or more of newly accumulated material can be readily detected by Sediment Profile Image (SPI) camera technology. If the spread of the apron material for LBC is considered excessive, placement operations could be modified to reduce dispersion.

Small fractions of suspended materials may settle and accumulate as a thin "veneer" on the bottom surrounding a CAD pit. Contaminated materials will be placed such that the thickness of newly accumulated material outside the lip of

the pit does not exceed 2 cm. If this threshold is exceeded, placement operations could be modified to reduce dispersion or the accumulated material could be capped as an apron deposit.

Cap materials

The USACE capping design guidance requires that any material used for a cap be acceptable for open water placement, as determined under the CWA regulations. These requirements are given in detail in the Inland Testing Manual. The corresponding state water quality certification would require that the cap material be acceptable for open water placement under the PSDDA framework.

Placement Methods for Caps

Placement of capping material must be accomplished so that the deposit forms a layer of the required thickness (as dictated by the cap design) over the contaminated material. Placement of a cap of required thickness over a large area may require spreading the material to some degree to achieve proper coverage. The S-4 functional design standards require that the primary cap materials be placed by hydraulic slurry release from a specified elevation above the bed and that they be released from the discharge pipe in an unclumped condition.

Equipment and placement techniques for capping material will be compatible with those used for contaminated material placement to avoid displacement of the previously placed contaminated material or excessive mixing of capping and contaminated material.

Capping material will be placed (spread) such that the cap is gradually built to the design thickness and excessive disturbance and displacement of the contaminated materials during capping is avoided. Sandy sediment is the most likely capping material, and sand caps have been successfully placed over fine-grained contaminated material. Since capping materials are not contaminated, water-column dispersion of capping material is not usually of concern (except to account for loss when slowly placing a sand cap), the use of submerged discharge for capping placement need only be considered from the standpoint of placement control.

Navigation and Positioning

State-of-the-art navigation and positioning equipment (i.e., DGPS) or microwave systems and techniques must be employed to control placement. Taut-moored buoys, mooring barges, various acoustical positioning devices, and computer assisted, real-time helmsman's aids should also be considered. In all cases, barges or scows must be required to release the material within prescribed

placement lanes or designated points of placement. Diligent inspection of operations to ensure compliance with specifications is essential.

Interim Cap Design

Considering the times required for recolonization and consolidation, a time lag of 4 weeks between completion of a given contaminated material placement and initiation of subsequent contaminated material placement or capping is considered acceptable. Interim cap placement is assumed to be required if there is a delay of more than 4 weeks between contaminated material placements over a specific area.

During 1999 and 2000, a project in Boston Harbor included capping in-channel CAD cells where fine-grained contaminated sediments with high water contents were placed. Results from this project have shown that an interval of up to several months or more can be required before weak contaminated sediments gain sufficient strength to support a 3-ft-thick sand cap (Fredette et al. 2000).

Design of the interim cap need not account for the long-term processes such as erosion that must be accounted for in a final cap design. Physical isolation, as discussed below under final cap design, is the primary requirement for an interim cap. Interim caps, if required, will consist of a minimum of 0.305-m (1-ft-) thickness of capping material.

Final Cap Design

The final cap will be designed using the latest USACE/EPA guidance for design of subaqueous dredged material caps (Palermo et al. 1998). The selection of a cap material and the thickness of placement will comprise the cap design. The cap will be designed with appropriate cap thickness components to account for physical isolation, bioturbation, erosion, and consolidation. The performance criteria related to cap design must be tied to suitable design objectives that the cap is intended to meet.

Physical isolation of the contaminated materials from benthic organisms to prevent bioaccumulation of contaminants is an appropriate design objective of the final cap. The minimum cap thickness to be maintained will be a 0.305-m (1-ft) thickness for physical isolation plus a thickness equivalent to the depth of significant bioturbation of marine organisms likely to colonize the site following closure. The total cap thickness will be the sum of the minimum cap thickness plus a component for erosion. The cap erosion thickness component will be equivalent to the greater of erosion calculated for period of 20 years of normal current/wave energies or that for the design storm event. The capping material is assumed to be a granular sandy sediment, therefore, no cap component for cap material consolidation is deemed necessary.

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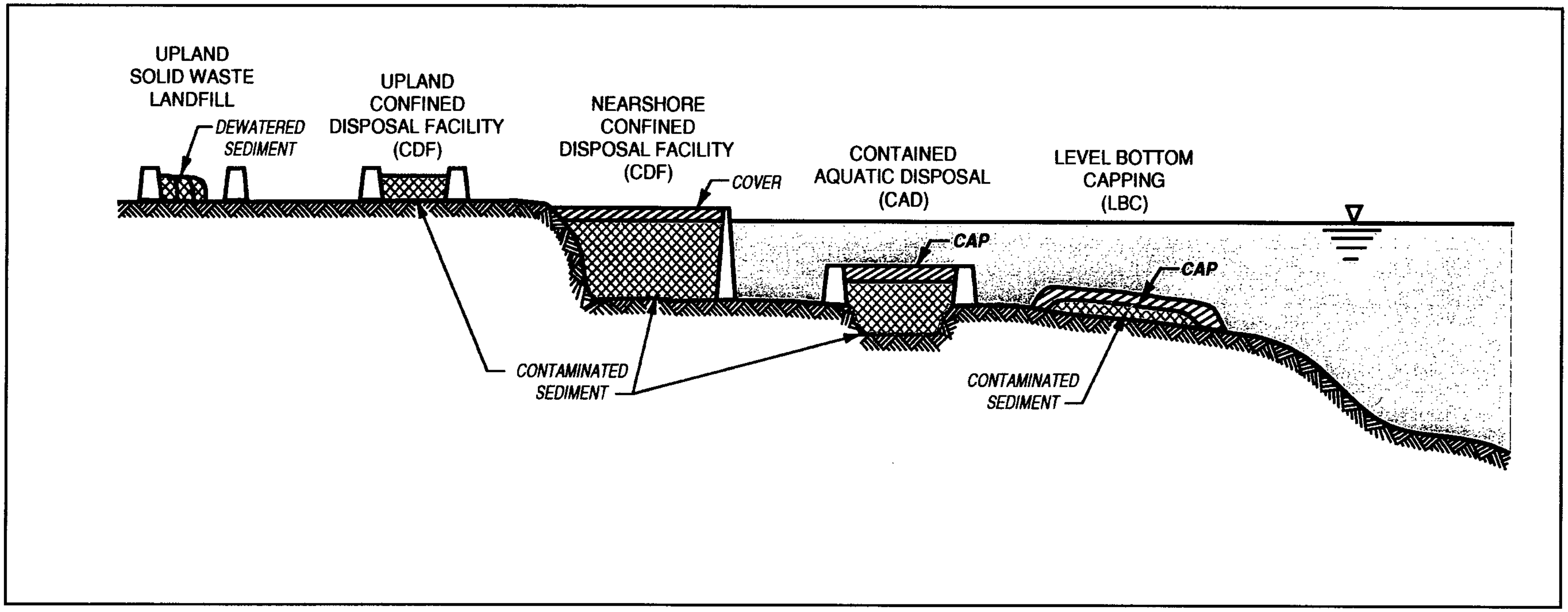

Figure 1. Conceptual illustration of MUDS alternatives

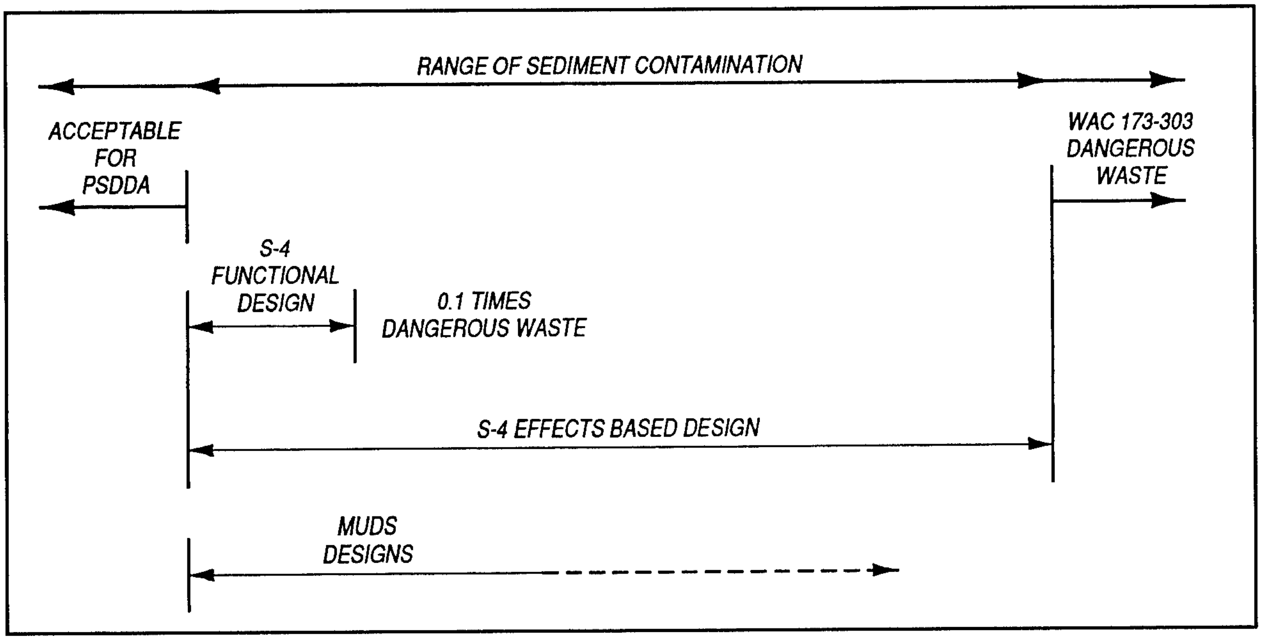

Figure 2. Relative levels of contamination for S-4 standards and the MUDS framework

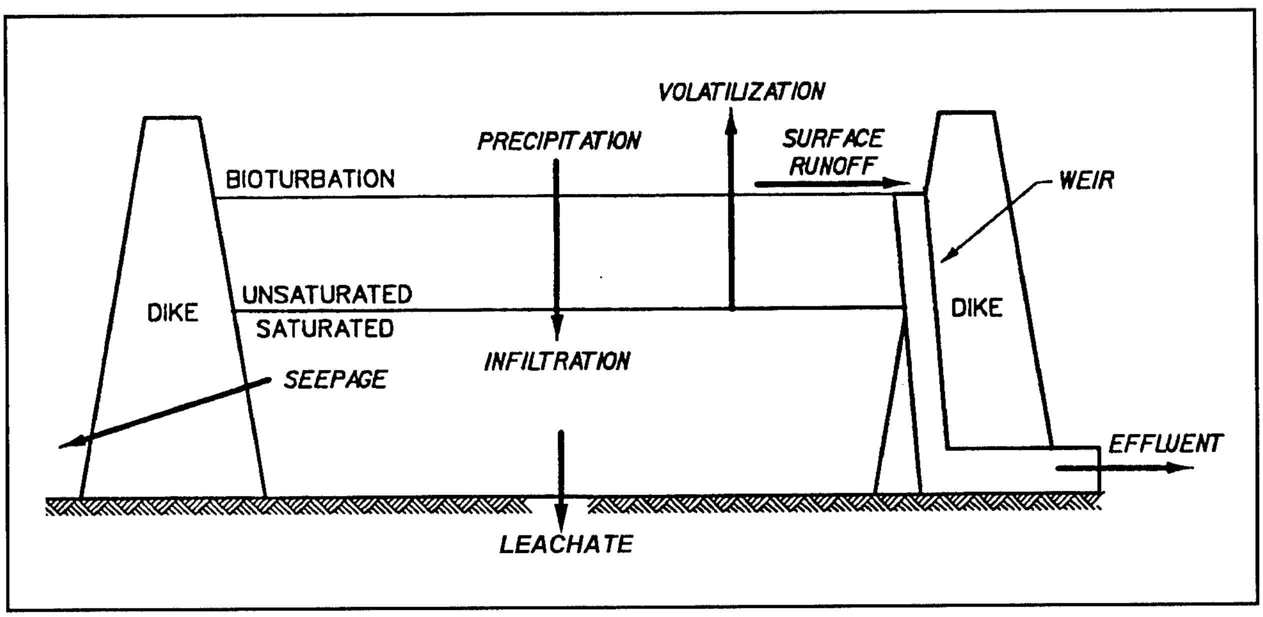

Figure 3. Contaminant pathways for upland CDFs

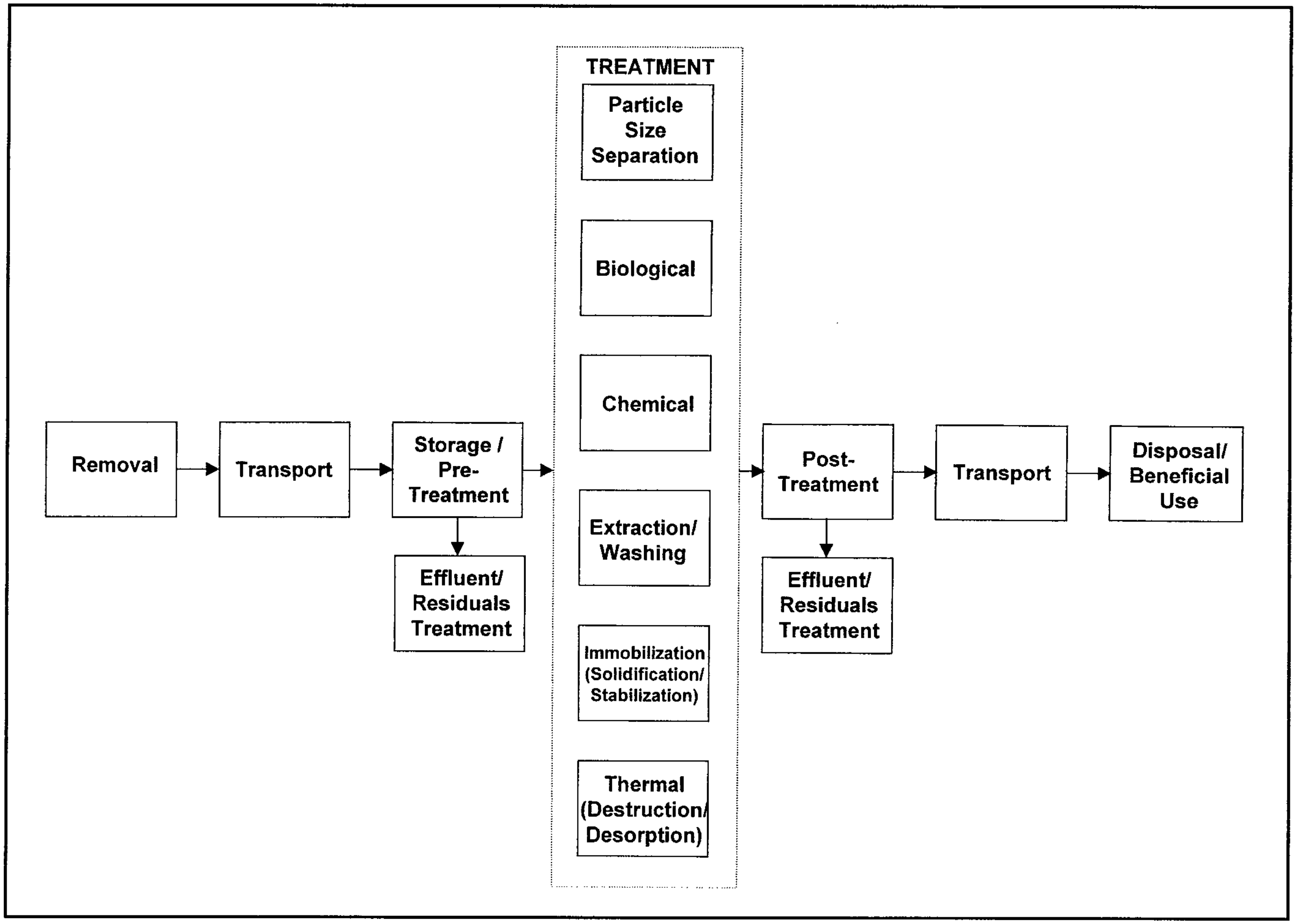

Figure 4. Process train for treatment of contaminated sediments

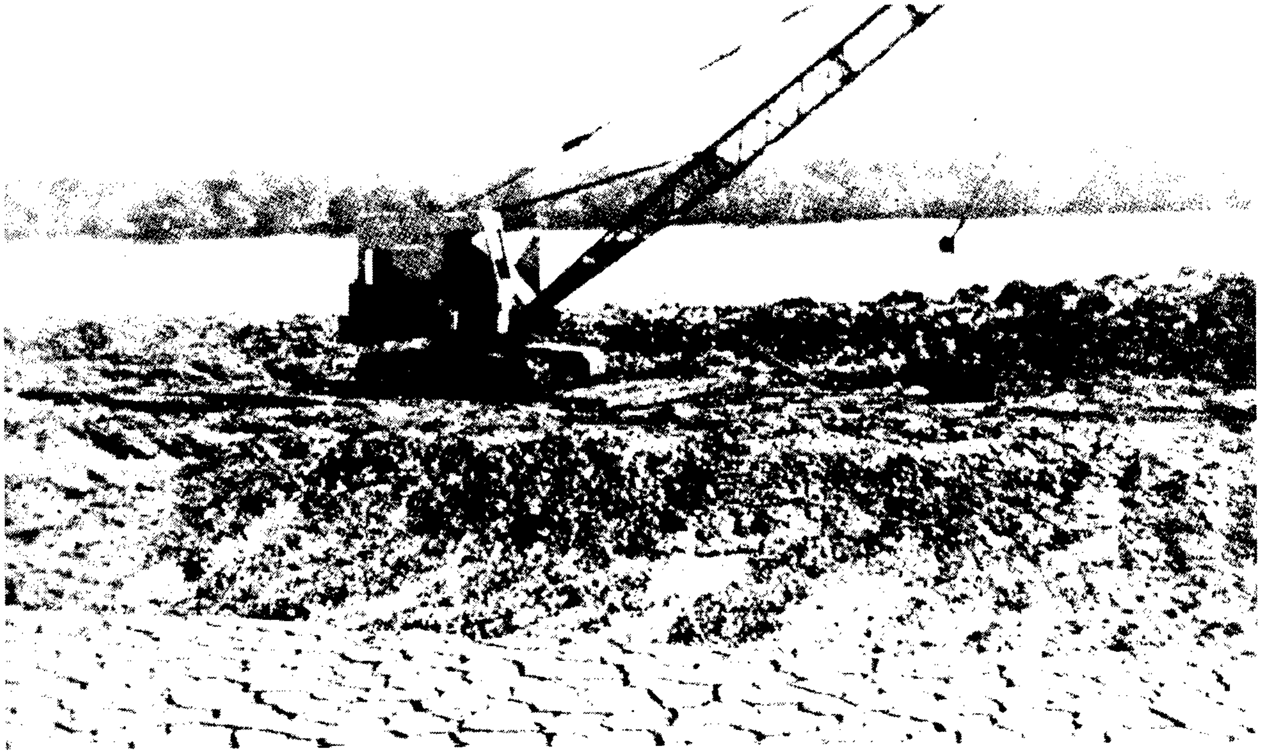

Figure 5. Small dragline operation for perimeter trenching

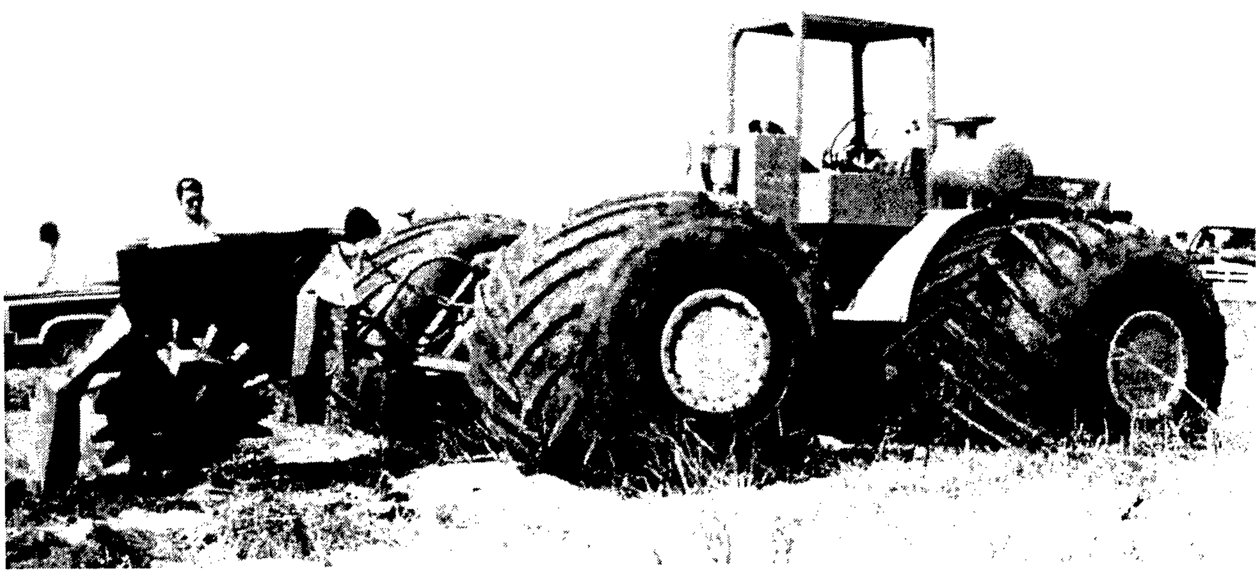

Figure 6. Rubber-tired rotary trencher

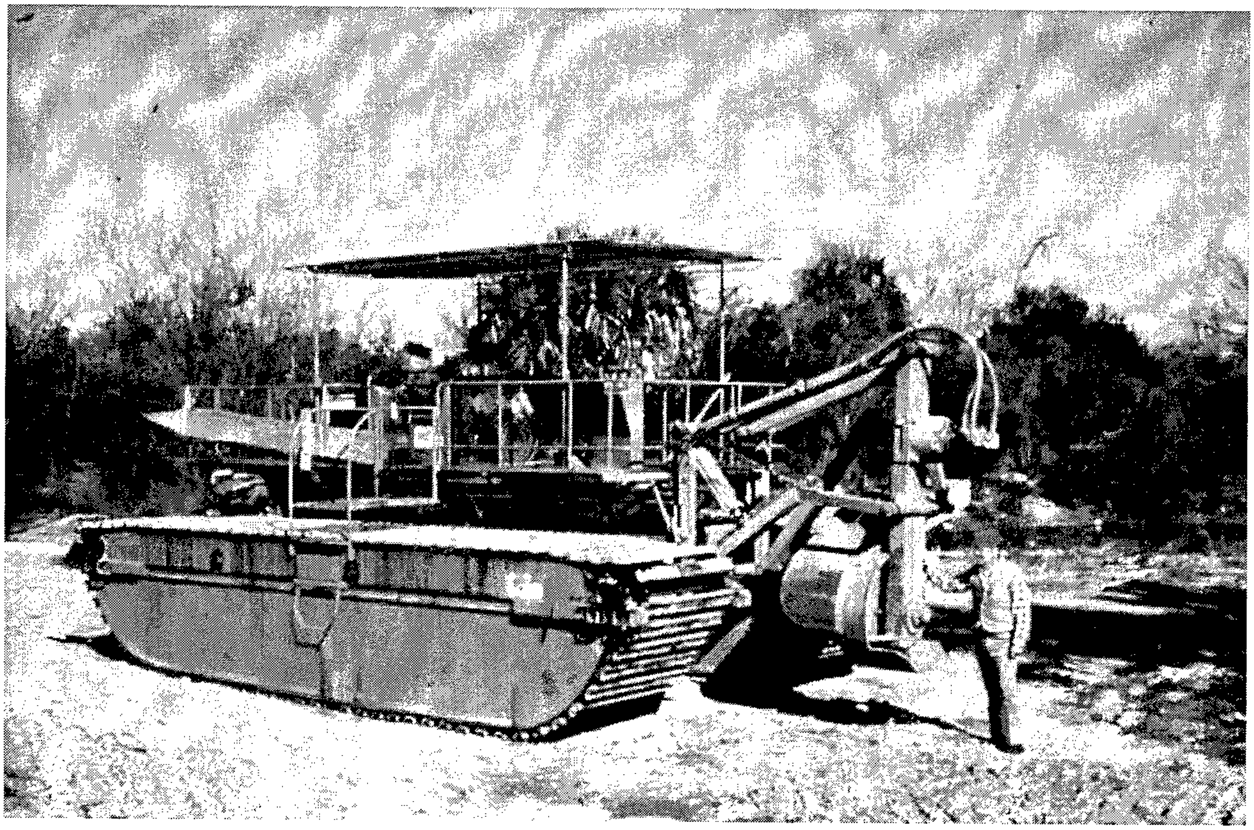

Figure 7. Track-mounted rotary trencher

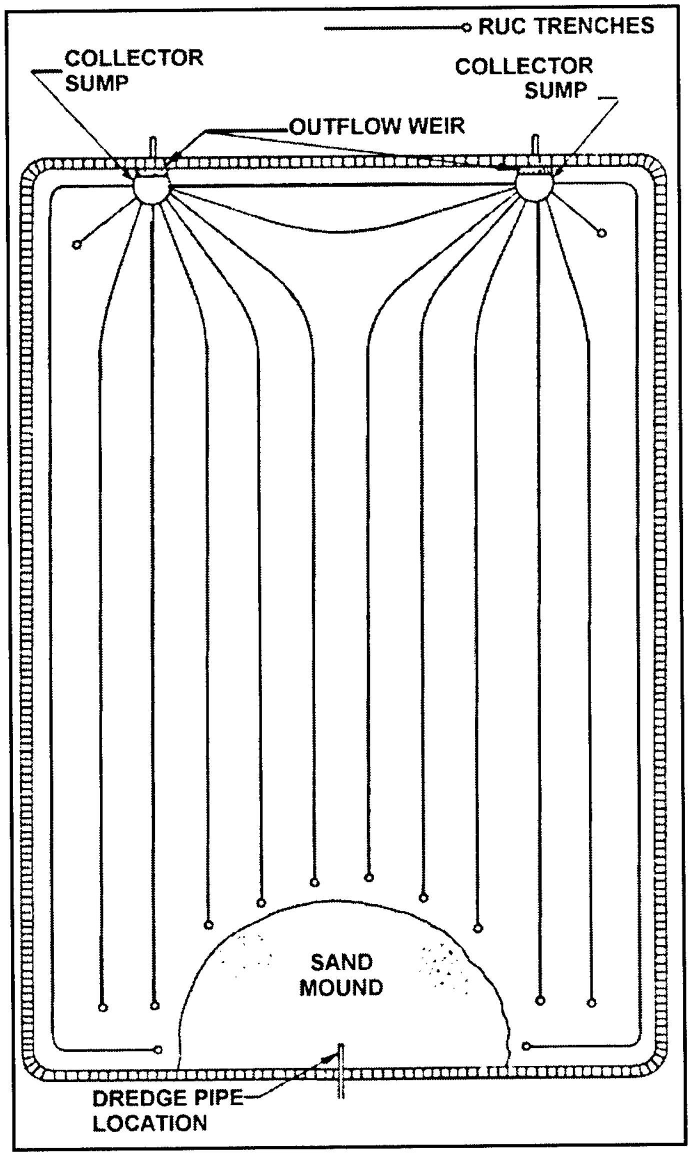

Figure 8. Combination radial-parallel trenching scheme (Riverine utility craft (RUC))

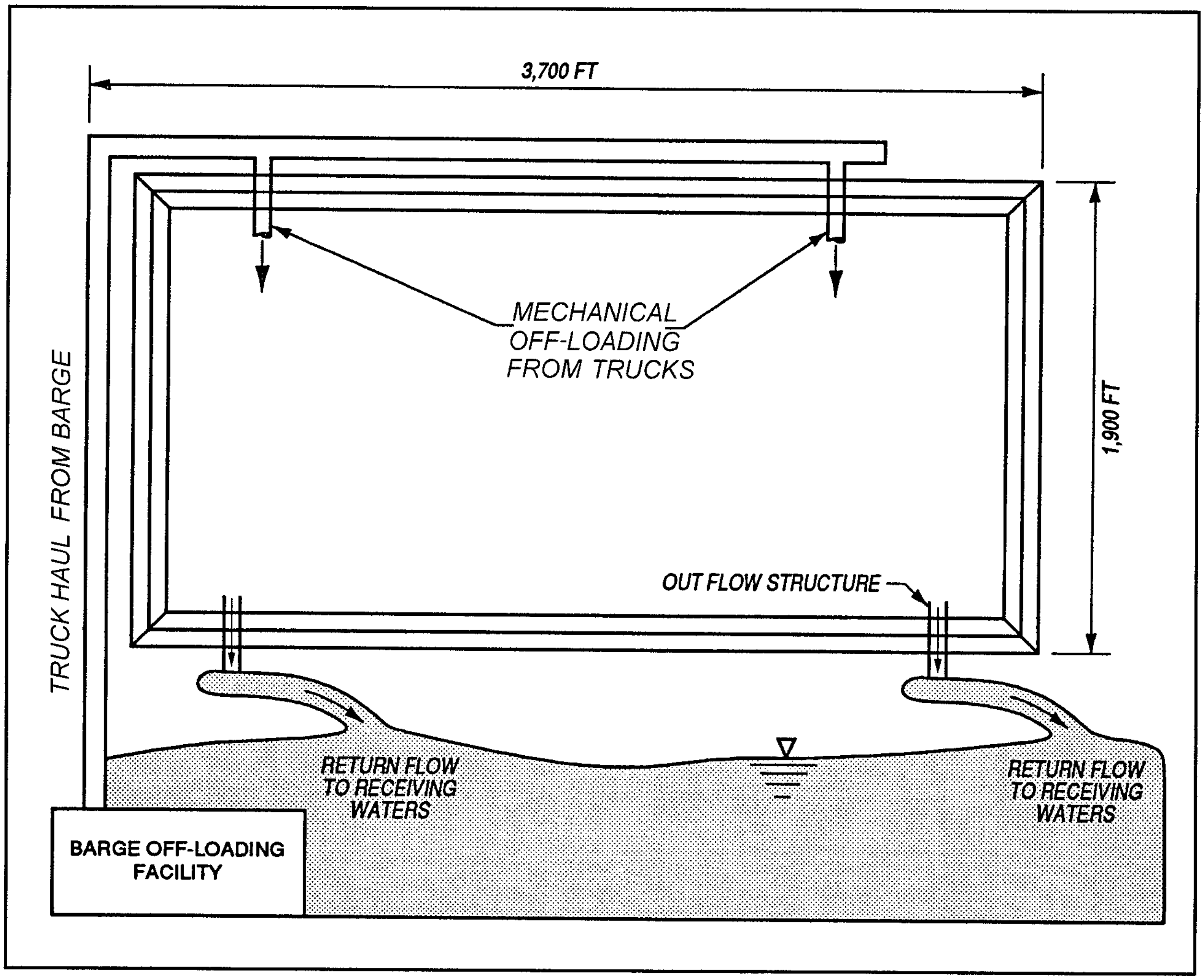

Figure 9. Overall dimensions and configuration for the upland CDF conceptual design (To convert feet to meters, multiply by 0.3048)

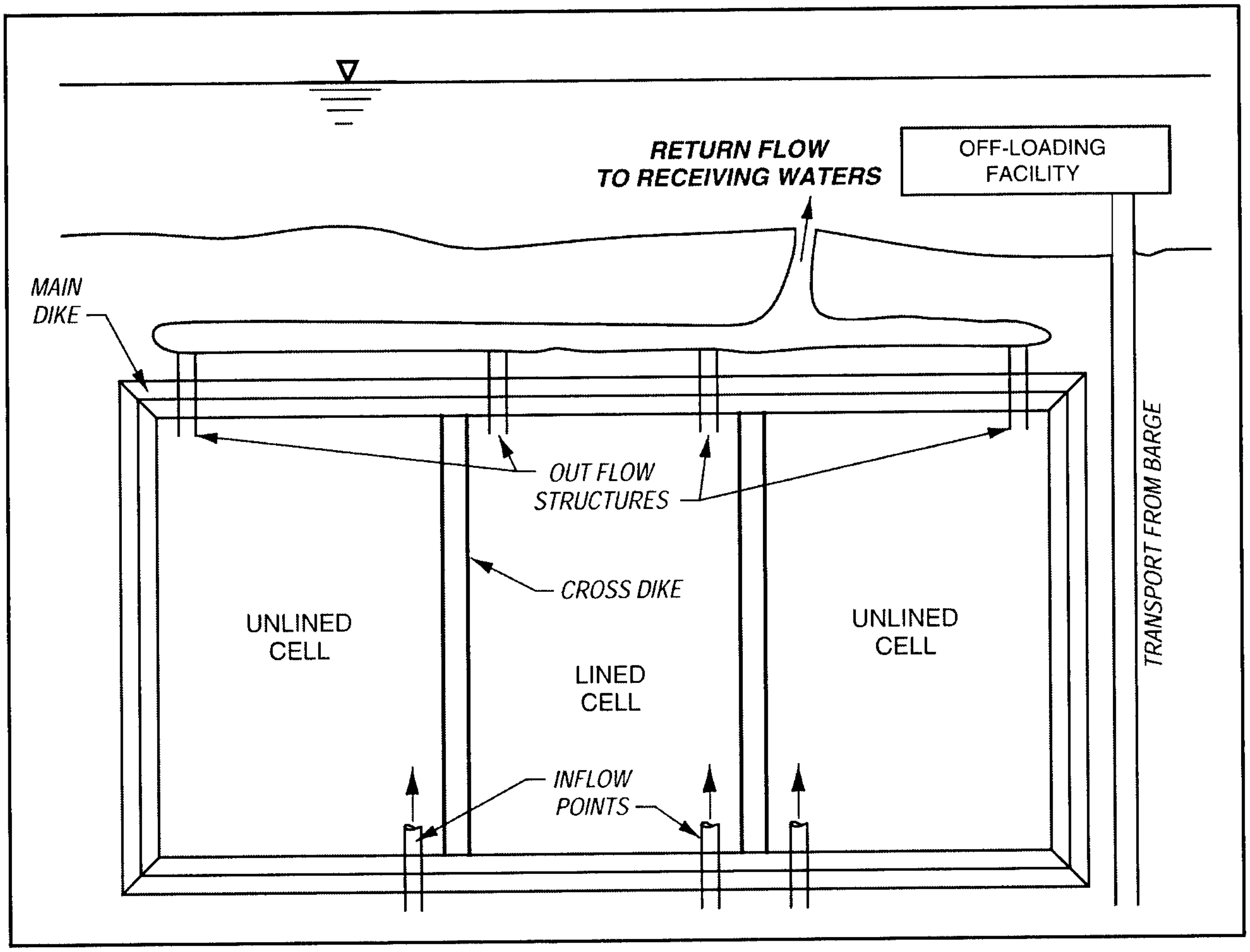

Figure 10. Configuration of multiple cell upland CDF conceptual design

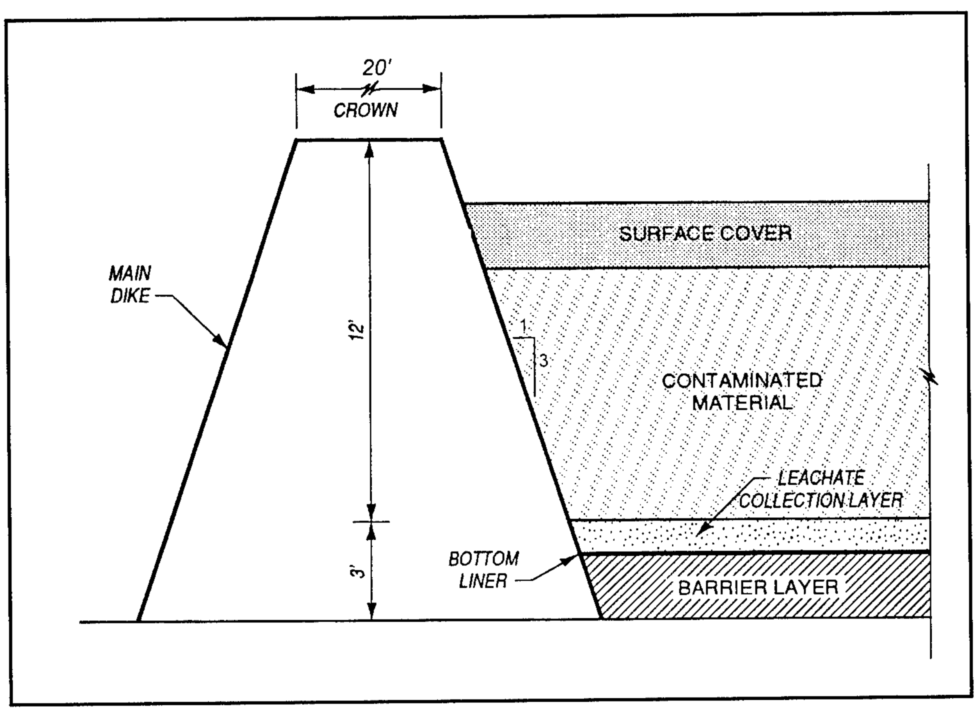

Figure 11. Cross section of the lined cell for upland CDF conceptual design (To convert feet to meters, multiply by 0.3048)

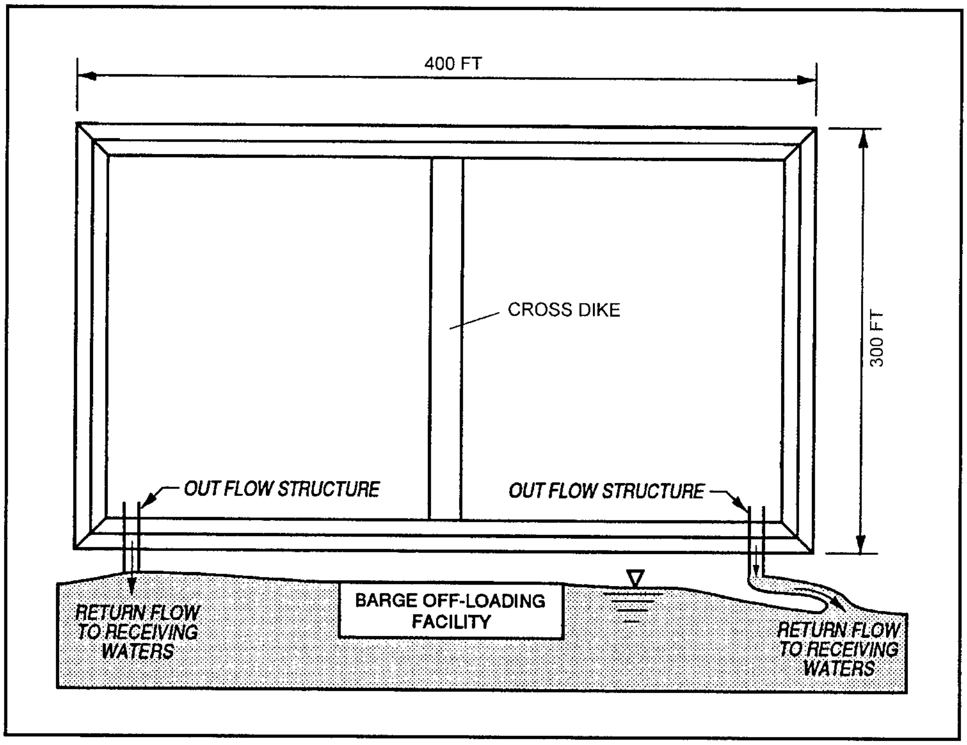

Figure 12. Overall dimensions and configuration for the upland rehandling and dewatering facility conceptual design (To convert feet to meters, multiply by 0.3048)

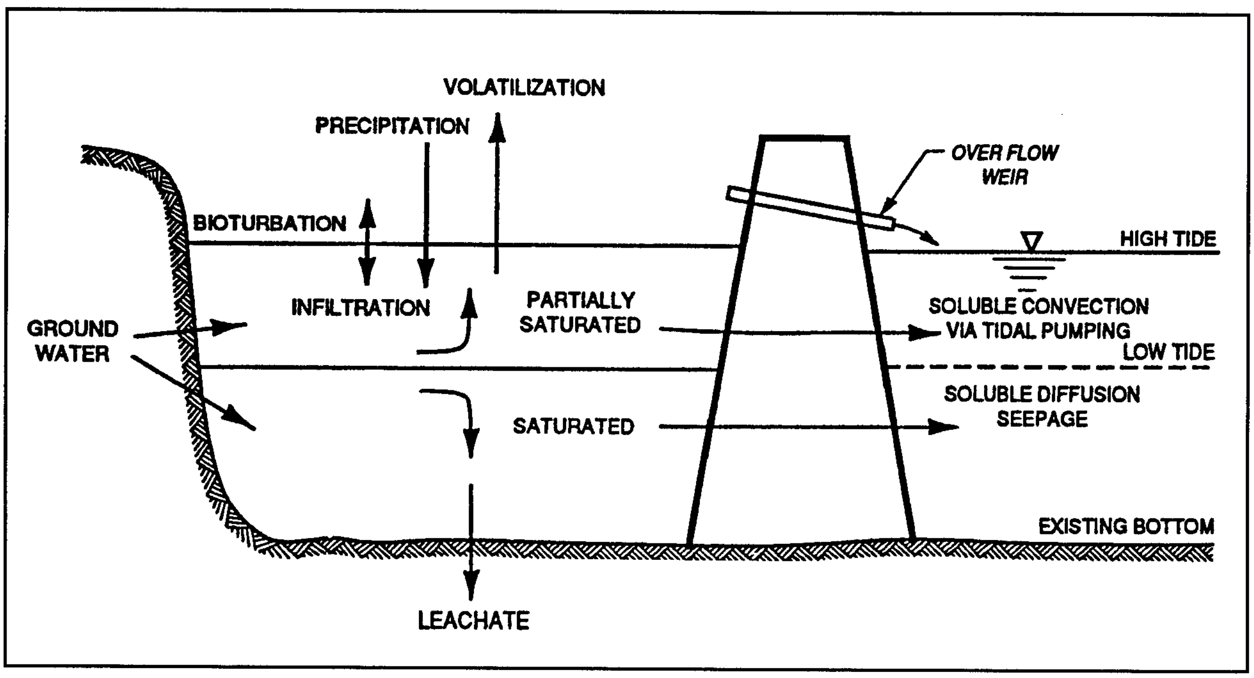

Figure 13. General contaminant pathways for nearshore CDFs

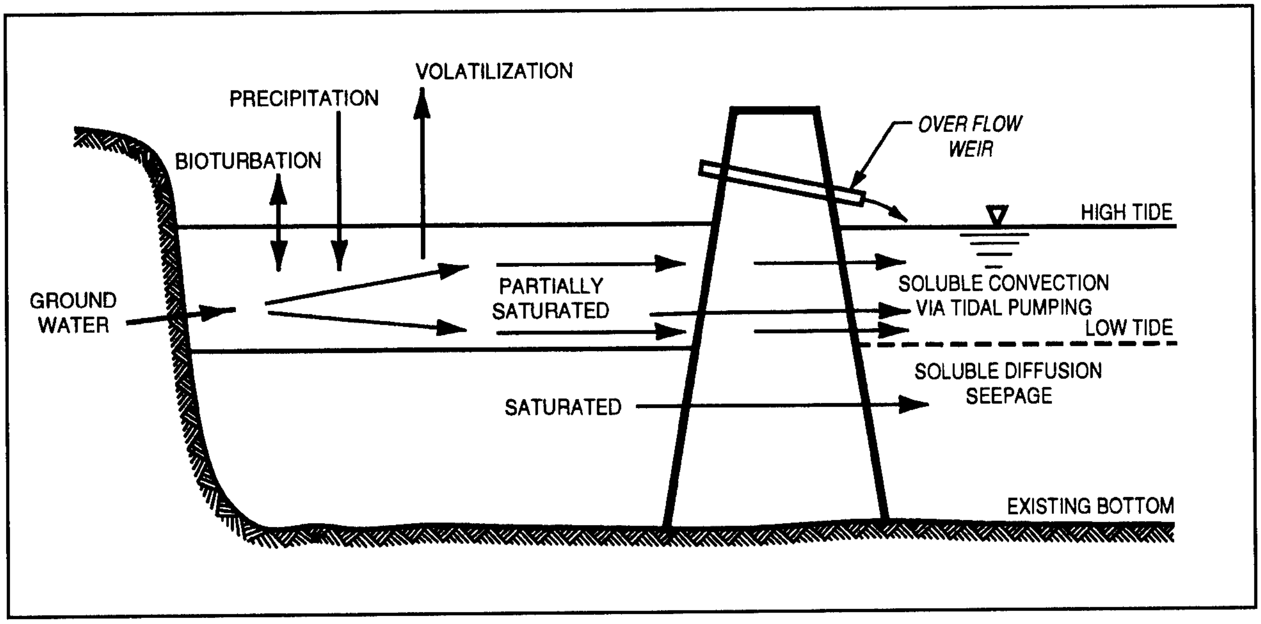

Figure 14. Primary contaminant pathways suggested for nearshore CDF's in Puget Sound

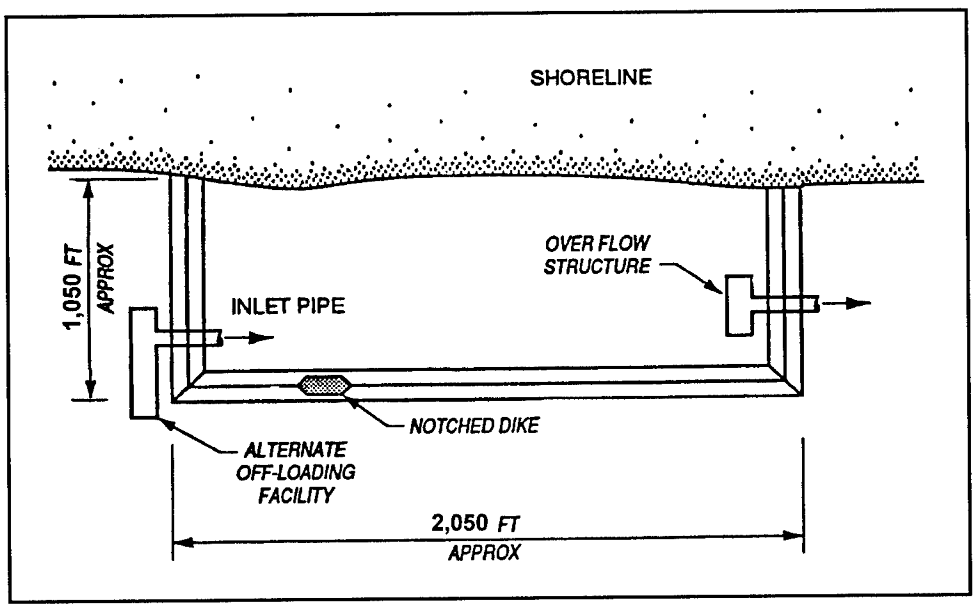

Figure 15. Overall dimensions and configuration for the nearshore CDF conceptual design 2,000,000 cu yd (To convert feet to meters, multiply by 0.3048; cubic yards to cubic meters, multiply by 0.7645549)

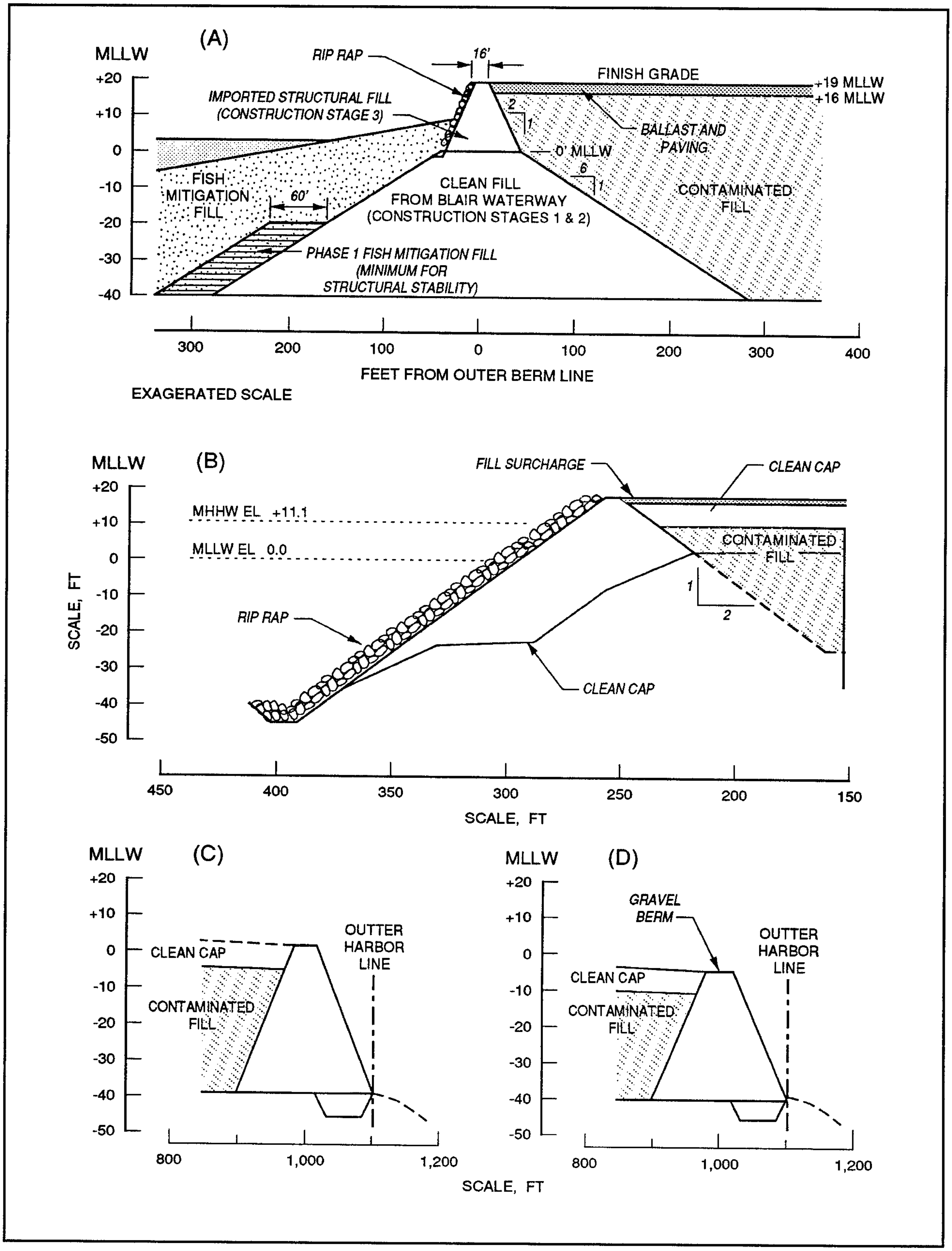

Figure 16. Cross section of the dike for the nearshore CDF conceptual design (To convert feet to meters, multiply by 0.3048)

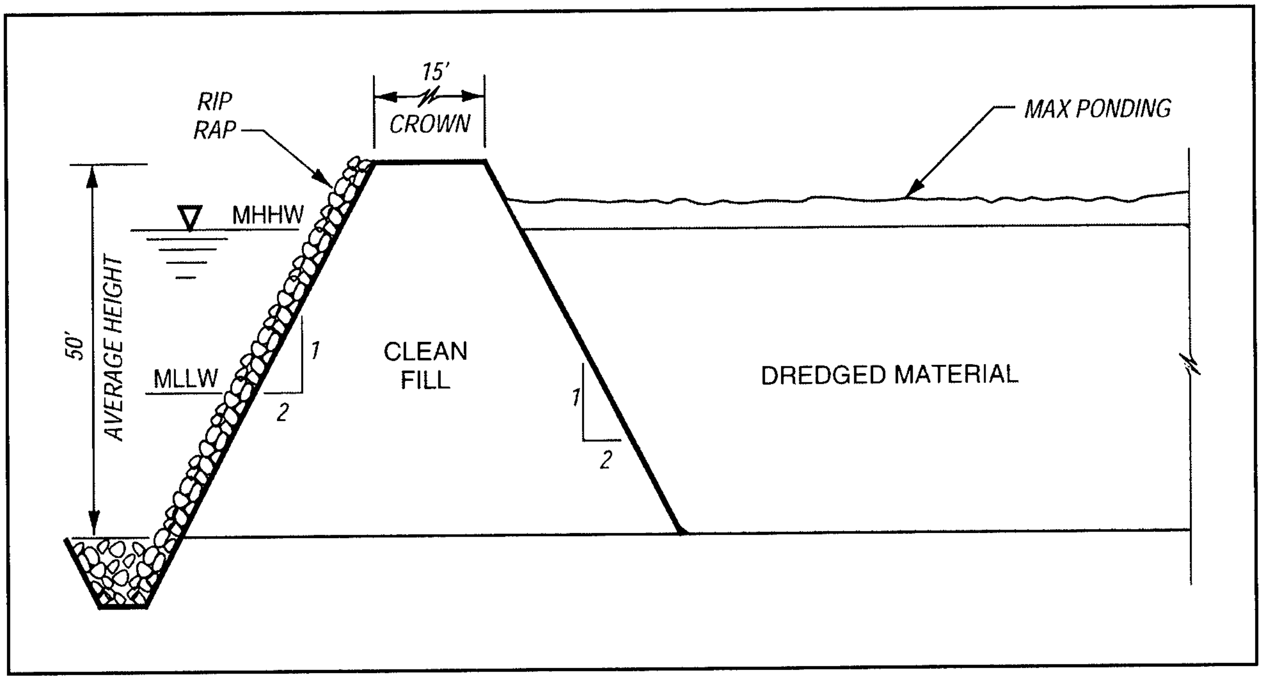

Figure 17. Typical cross sections of nearshore dikes designed and/or constructed in Puget Sound (To convert feet to meters, multiply by 0.3048)

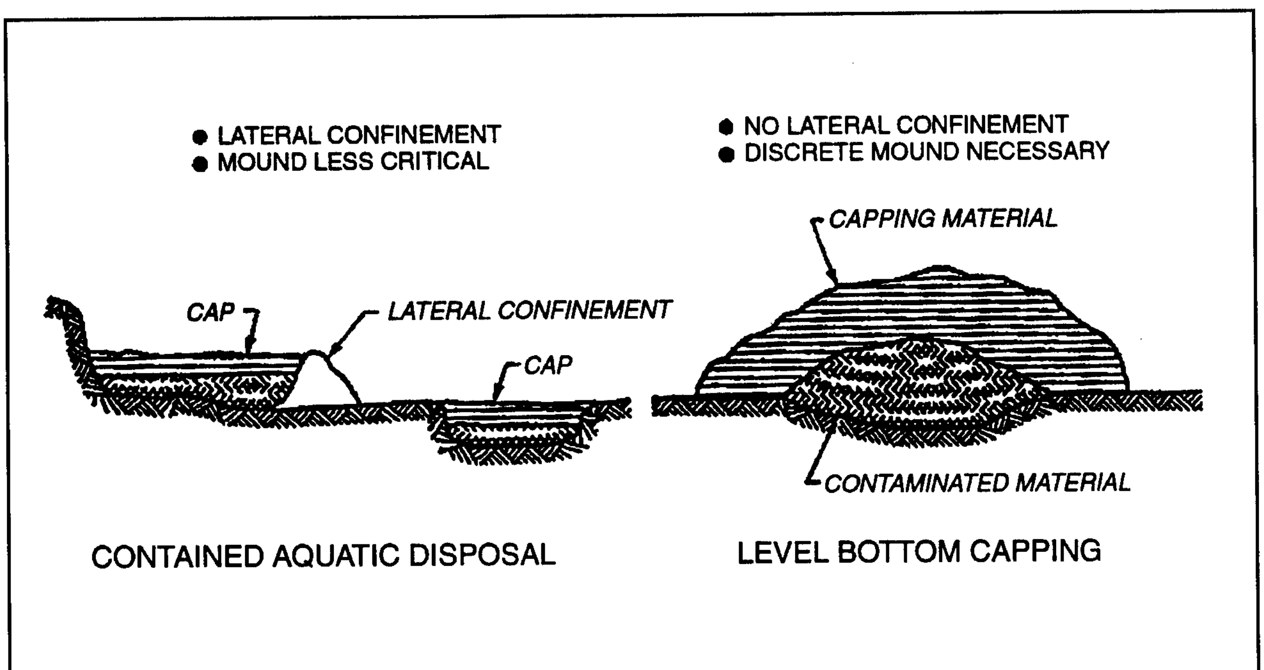

Figure 18. Illustration of LBC and CAD

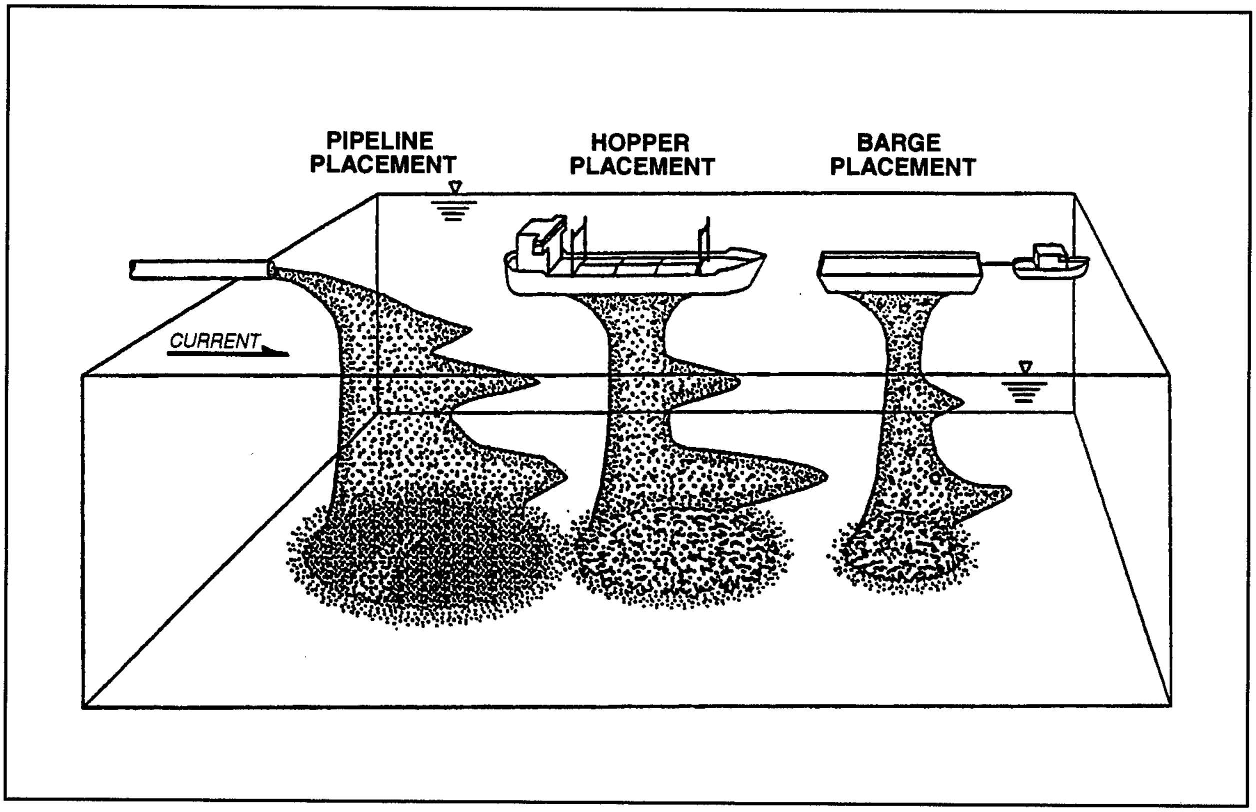

Figure 19. Conventional open water placement for capping

Figure 20. Spreading technique for capping by barge movement

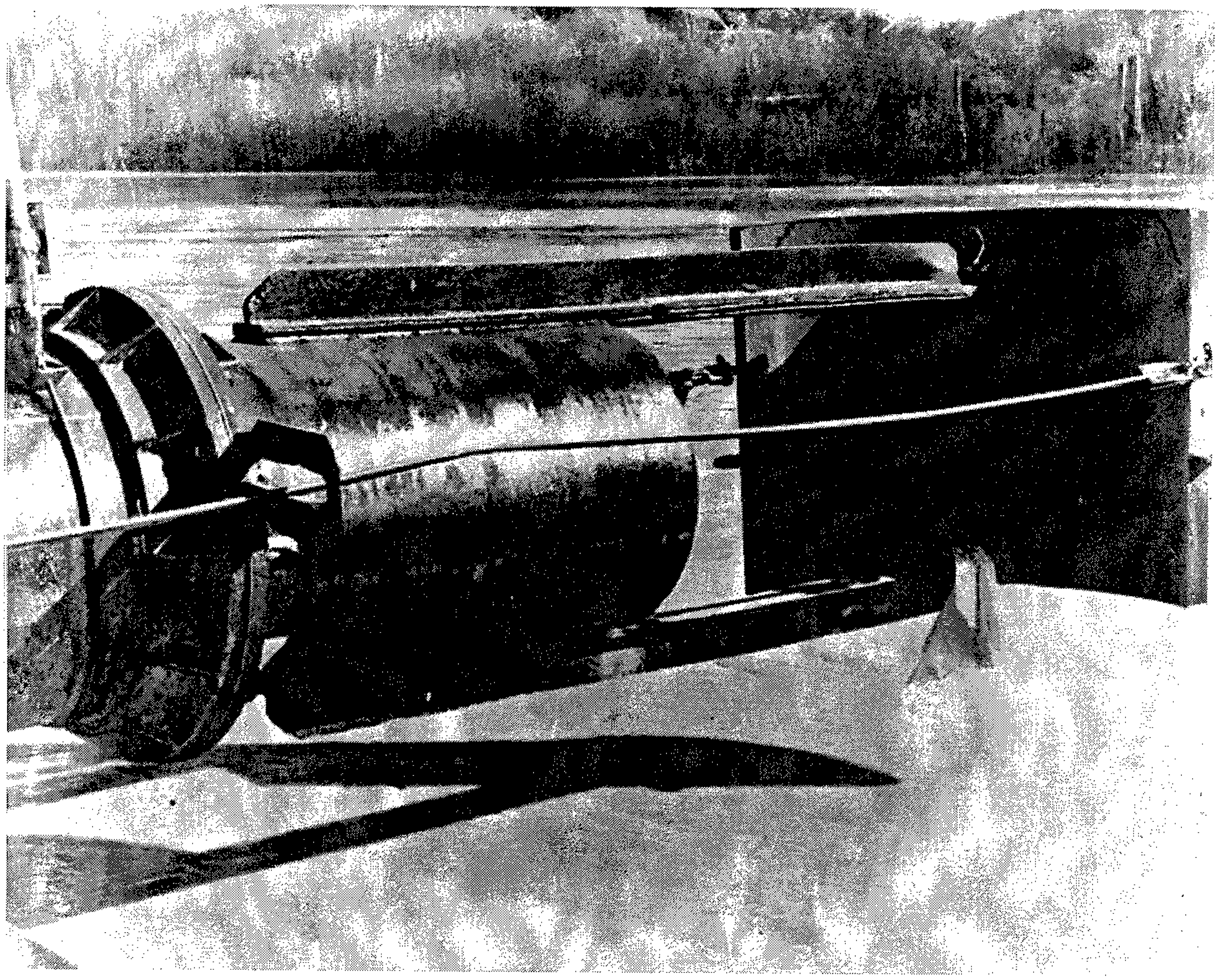

Figure 21. Spreader plate for hydraulic pipeline discharge

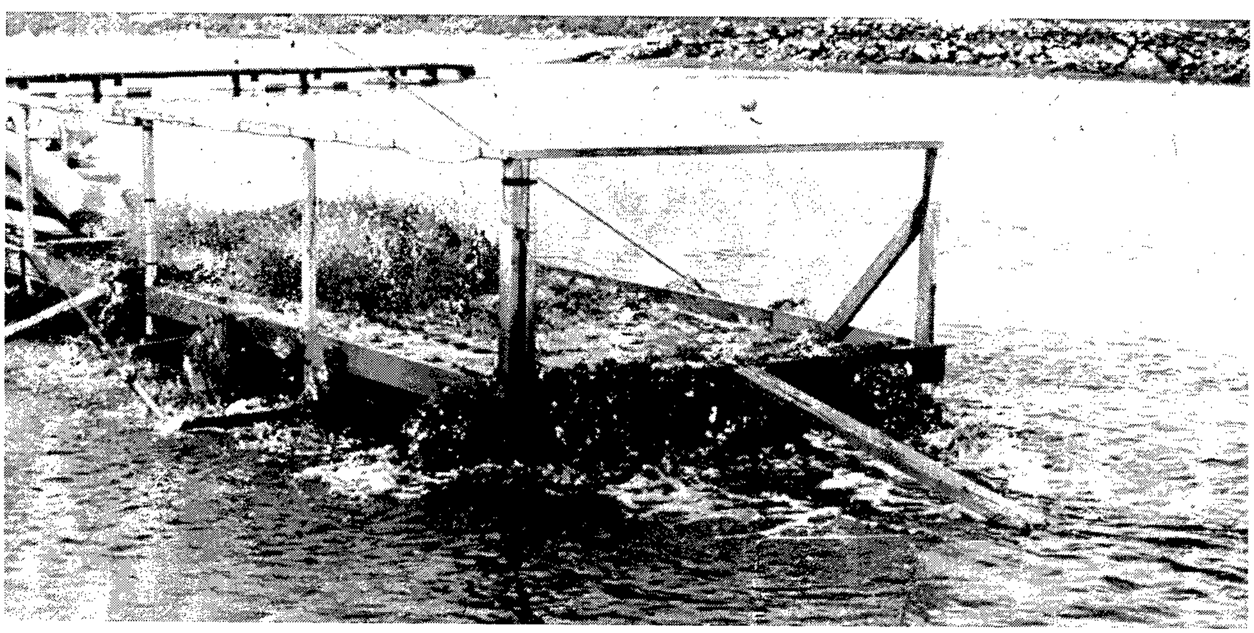

Figure 22. Spreader box or “sand box” for hydraulic pipeline discharge

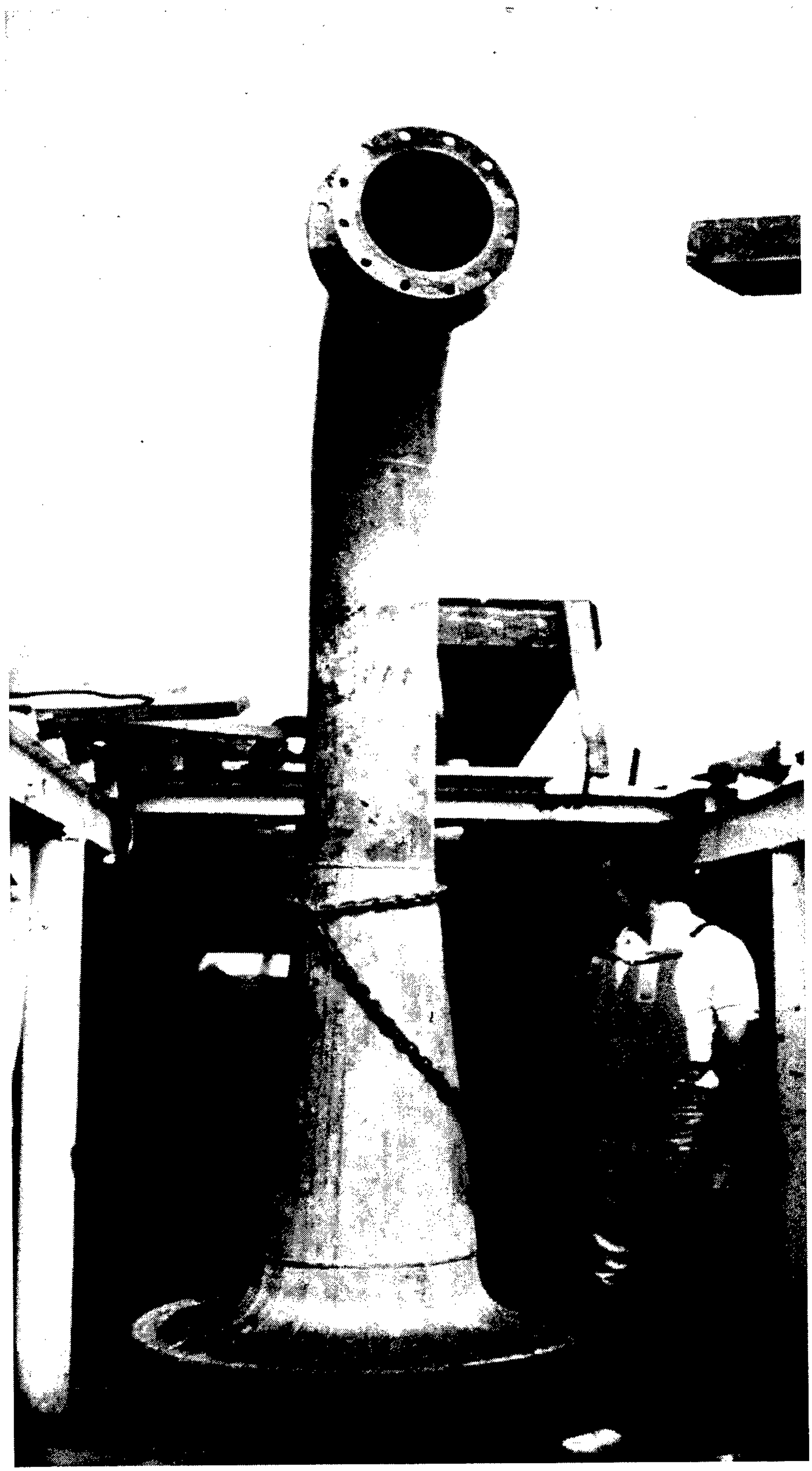

Figure 23. Photo of submerged diffuser

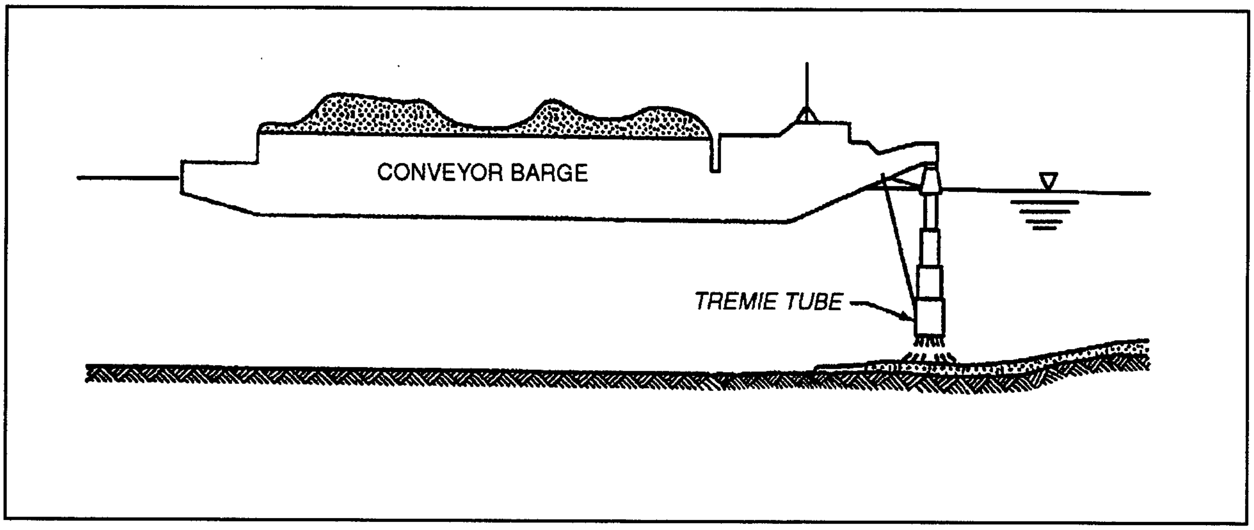

Figure 24. Conveyor unloading barge with tremie (from Togashi 1983)

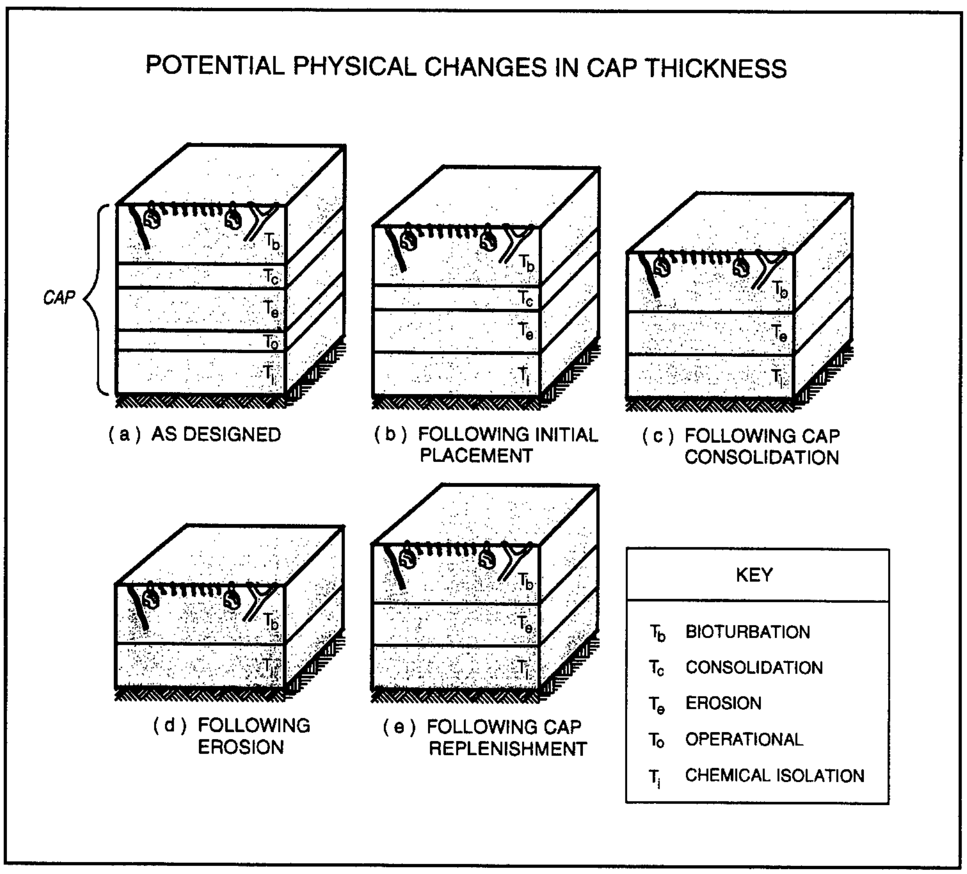

Figure 25. Schematics of cap thickness components and potential physical changes in cap thickness

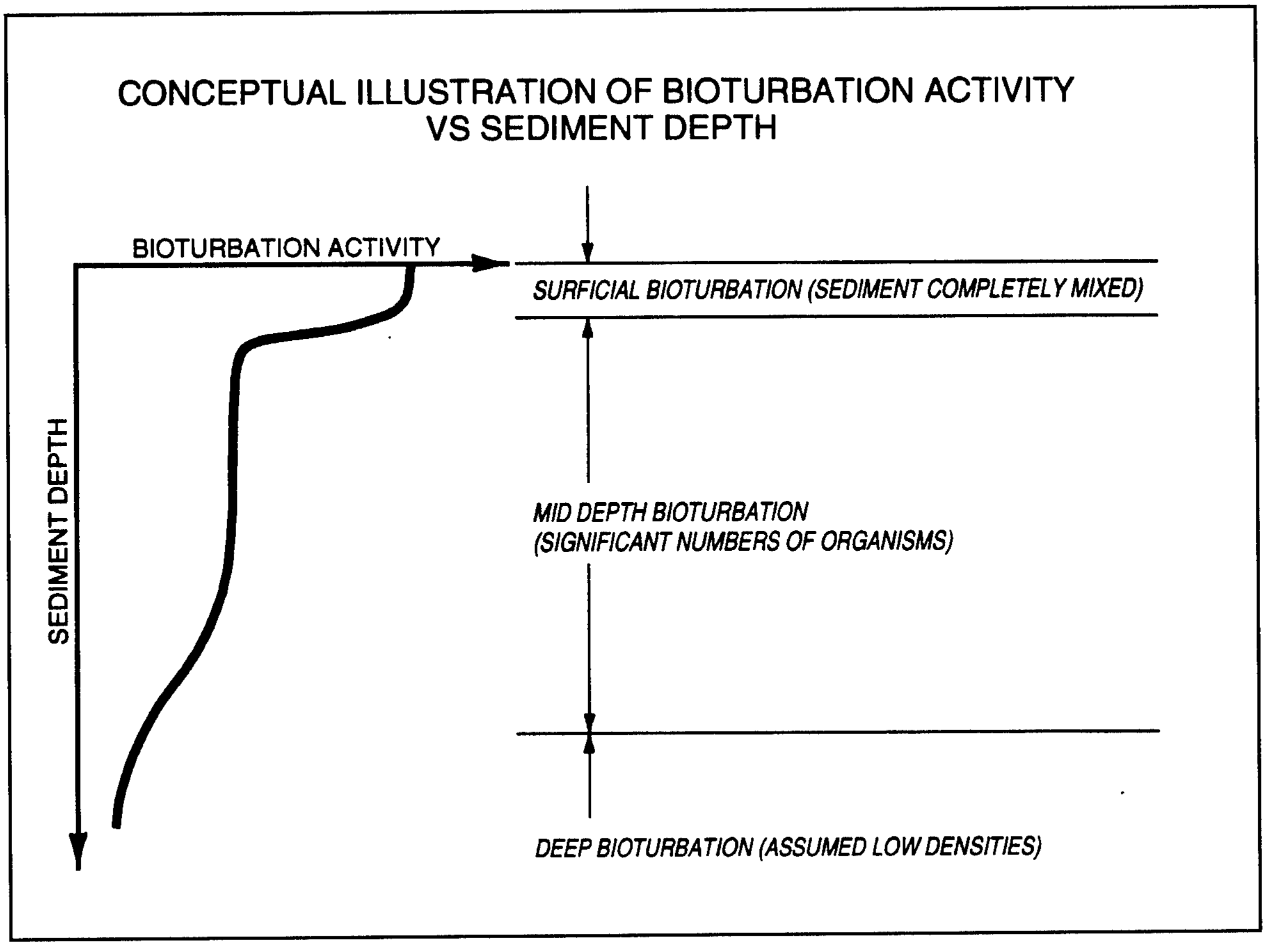

Figure 26. Conceptual illustration of bioturbation activity versus sediment depth

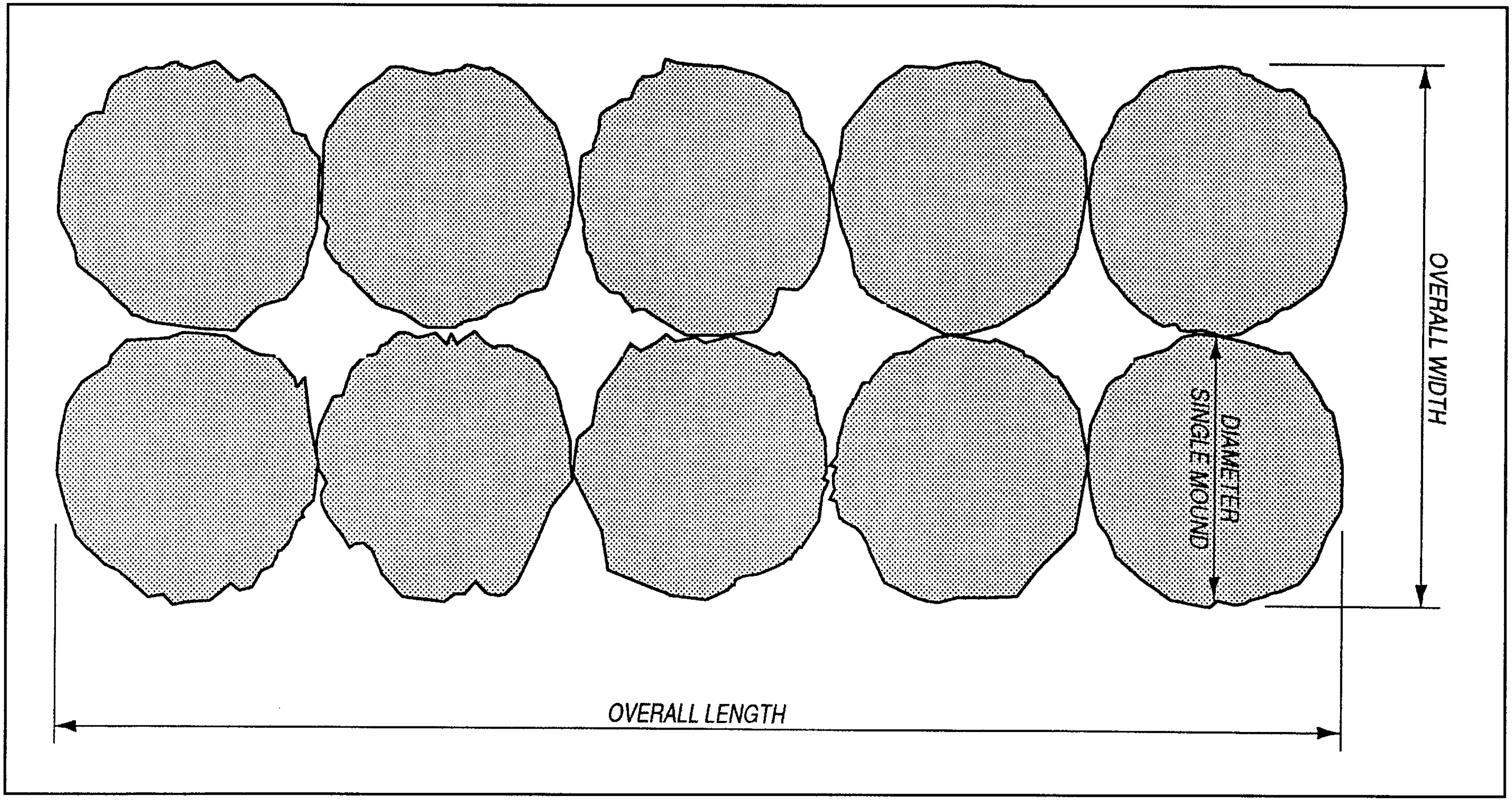

Figure 27. Layout for conceptual design of LBC mounds

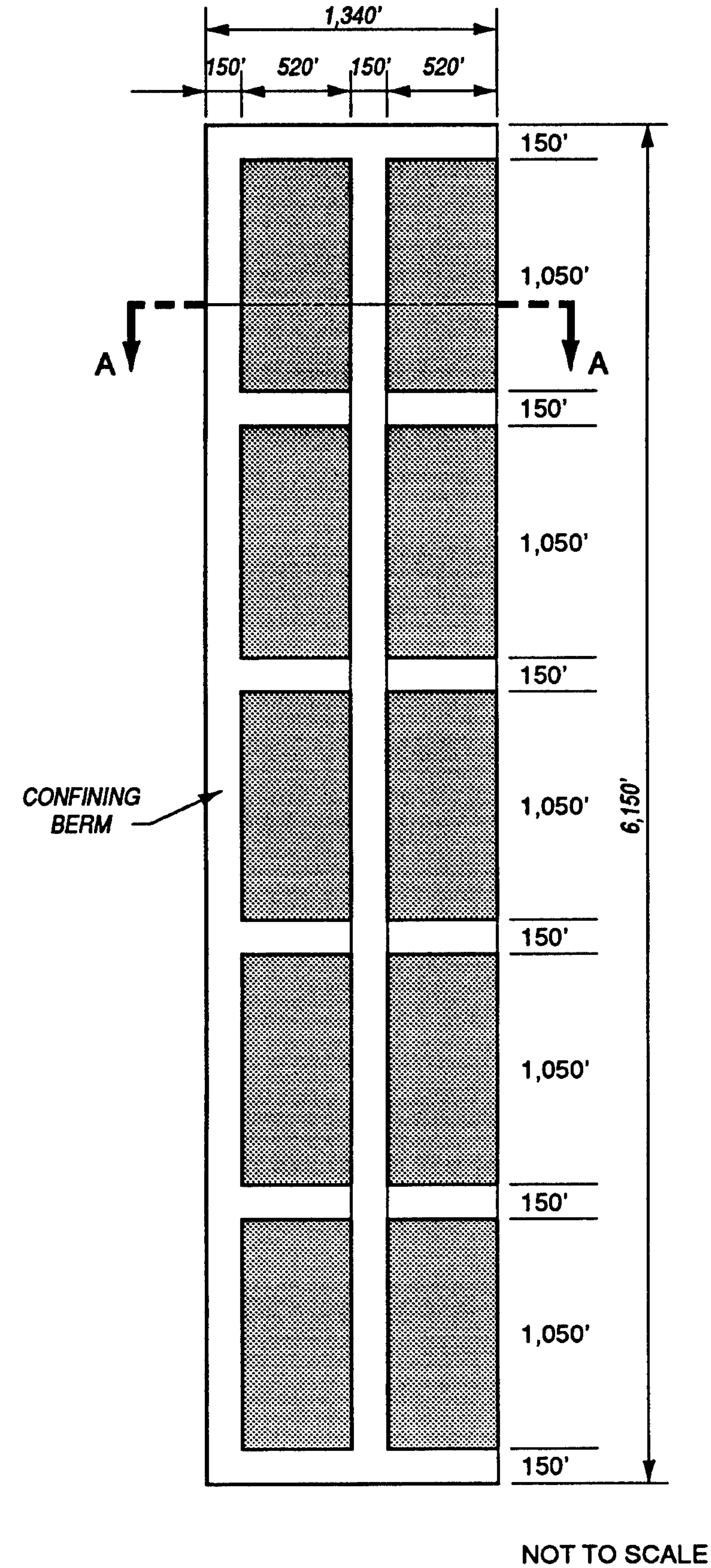

Figure 28. Layout for conceptual design of CAD pits (To convert feet to meters, multiply by 0.3048)

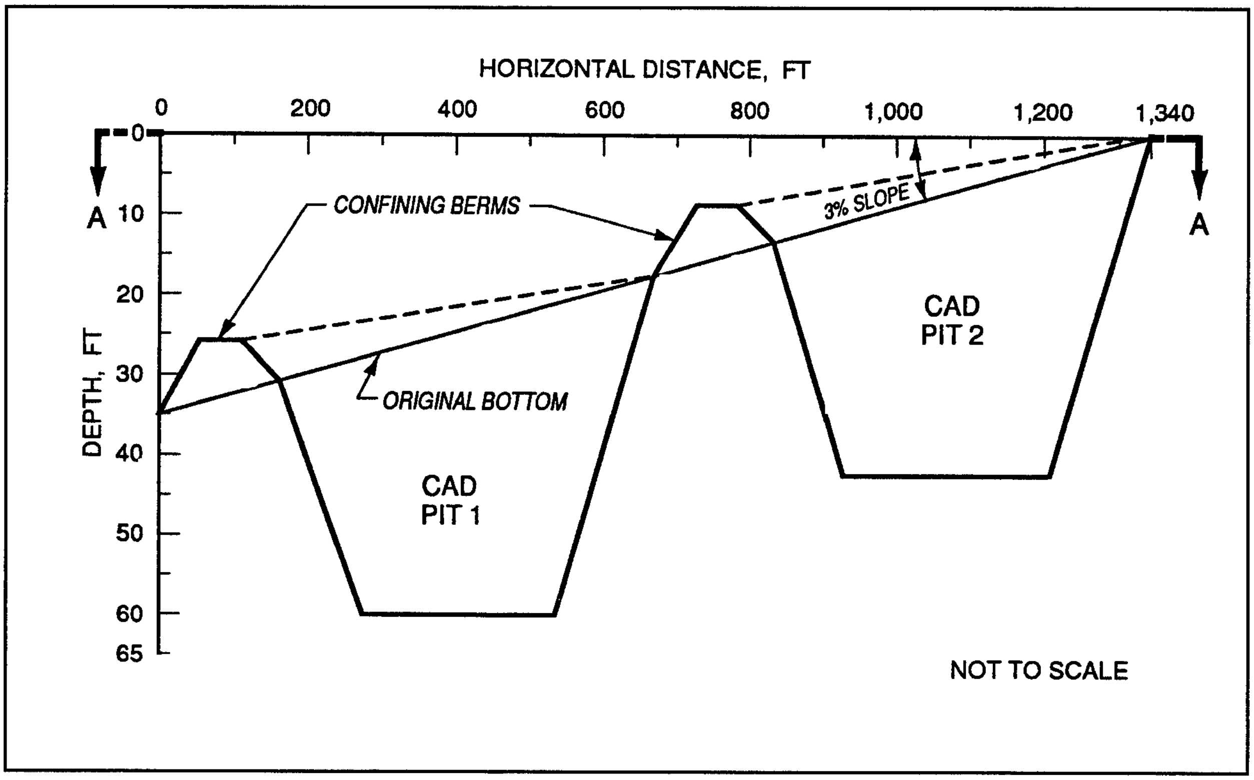

Figure 29. Cross section of CAD pits for conceptual design (To convert feet to meters; multiply by 0.3048)

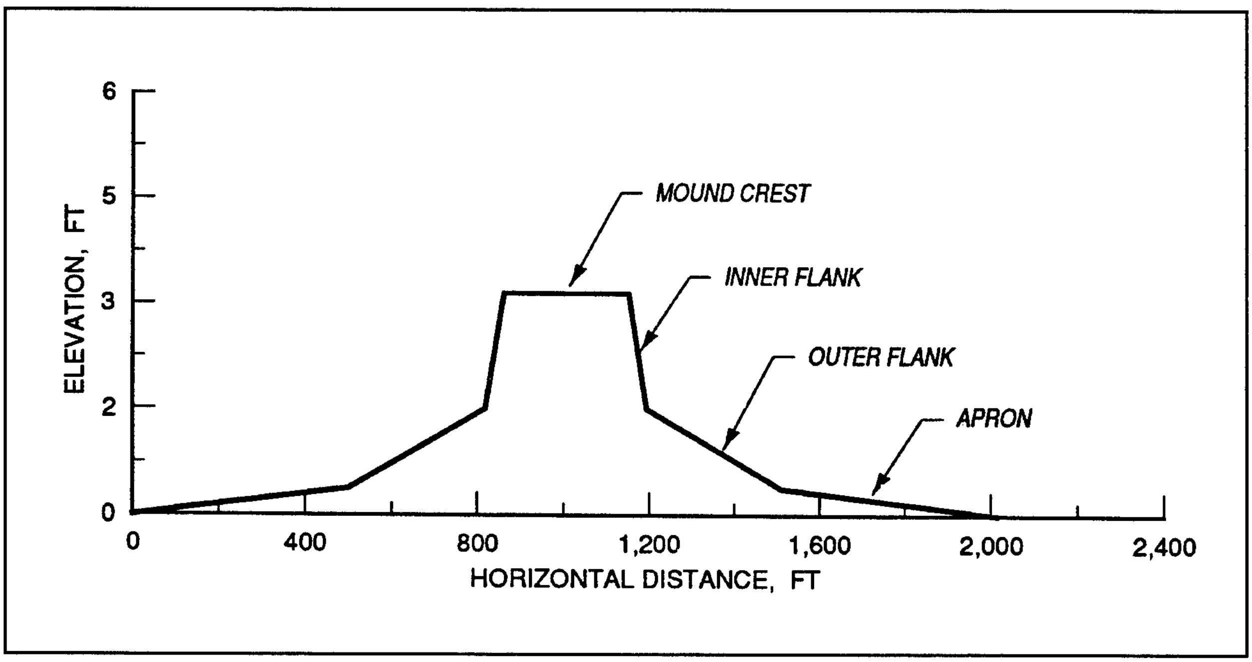

Figure 30. Cross section of LBC mound for conceptual design (To convert feet to meters, multiply by 0.3048)

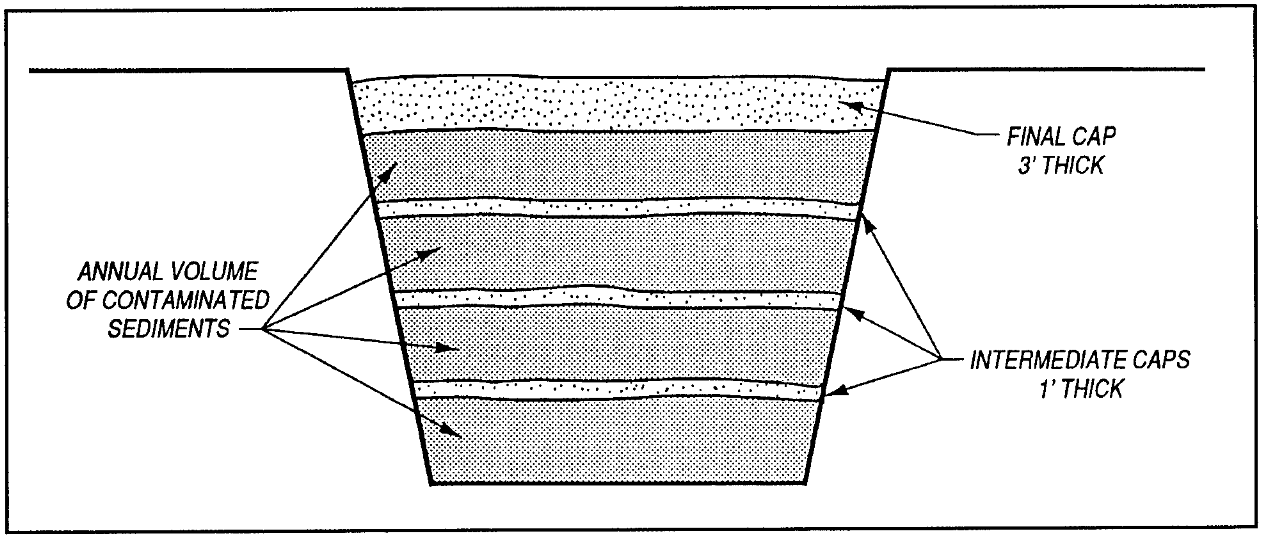

Figure 31. Cross section of single CAD pit showing intermediate and final caps (To convert feet to meters, multiply by 0.3048)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
July 2000

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Multiuser Disposal Sites (MUDS) for Contaminated Sediments from Puget Sound – Subaqueous Capping and Confined Disposal Alternatives

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Michael R. Palermo, James E. Clausner, Michael G. Channell, Daniel E. Averett

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Environmental Laboratory and Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC TR-00-3

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Engineer District, Seattle
P.O. Box 3755
Seattle, WA 98124-2255

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army Engineer District, Seattle (CENWS), is participating in the Puget Sound Confined Disposal Site Study. This study is aimed at determining the feasibility of establishing a system of multiuser disposal sites (MUDS) for disposal of contaminated sediments dredged from Puget Sound. Most of the contaminated sediments within Puget Sound are located within the central portion of the sound and are associated with environmental cleanup projects directed through Federal or state enforcement actions, projects with restoration of aquatic habitat as their primary purpose, and dredging of Federal and non-Federal navigation channels.

The feasibility evaluation will be conducted in phases. The initial programmatic phase resulted in a programmatic Environmental Impact Statement (PEIS). Site-specific evaluations along with a site-specific PEIS will be conducted in subsequent phases. Disposal alternatives that will be evaluated include: (a) level bottom capping and contained aquatic disposal (CAD), (b) nearshore (or island) confined disposal facilities (CDFs), (c) upland (CDF) disposal, (d) disposal in solid waste landfills, and (e) multiuser access to larger fill projects.

CENWS requested support from the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC), Environmental Laboratory, Vicksburg, MS, in conducting the feasibility evaluations. This report describes various subaqueous capping and confined (diked) disposal alternatives and provides conceptual designs and design and performance standards for these alternatives.

(Continued)

15. SUBJECT TERMS

CAD	CDF	Contained aquatic disposal	Dredged material	Nearshore	Sediment
CAP	Confined disposal	Contaminated	Dredging	Puget Sound	Upland

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED		UNCLASSIFIED		201	

14. (Concluded).

The disposal alternative descriptions and conceptual designs include the purpose, technical basis, and field experiences associated with each design feature or management technique, as well as how the technique could be applied within the context of a MUDS in Puget Sound. This report is intended to provide information which was directly integrated into the draft PEIS.